Inertial Fusion Driven by Heavy-Ion Beams*

W M Sharp and the HIFS-VNL team

9 February 2011

BERKELEY LAB

Fusion Energy Sciences

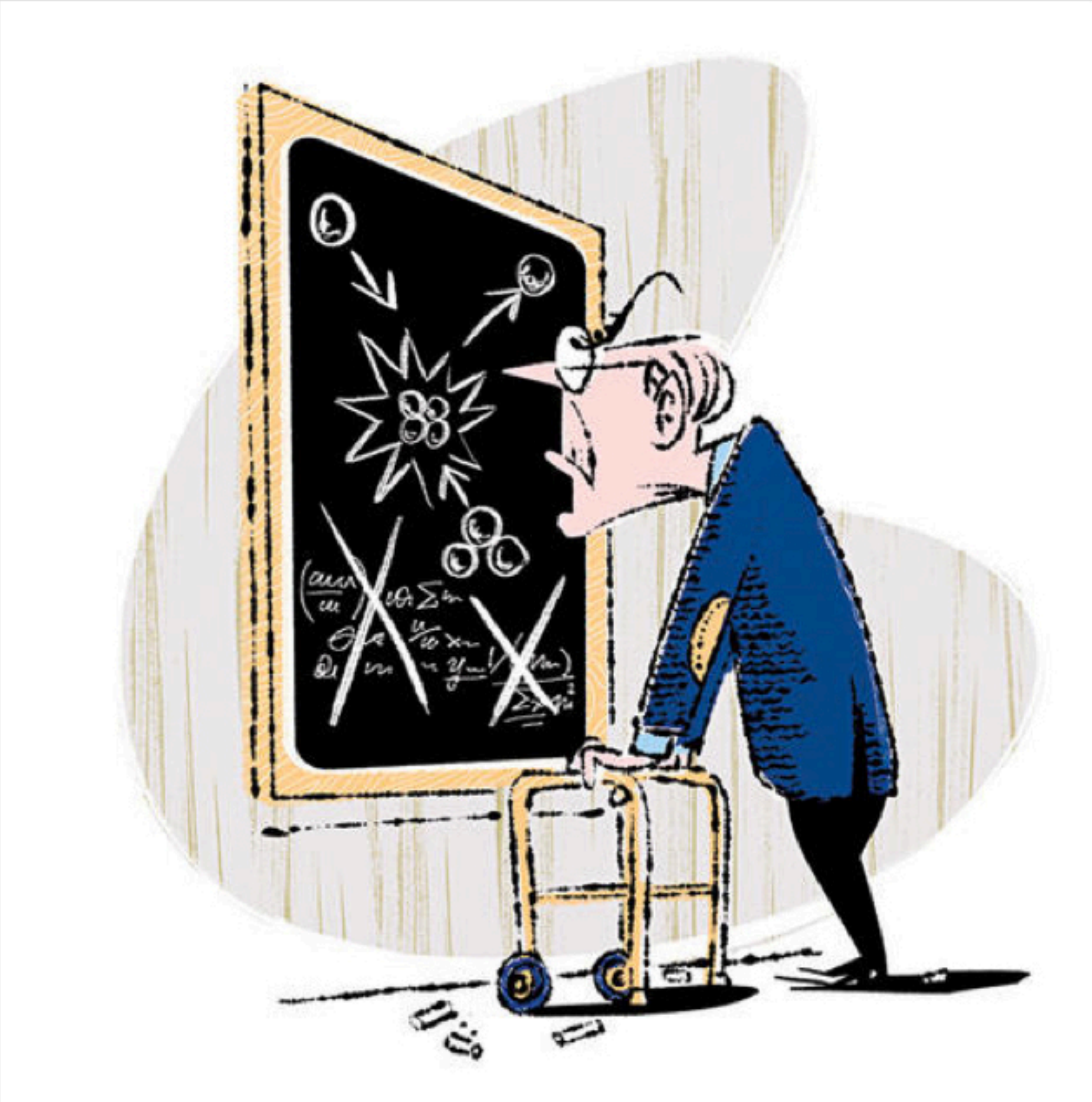
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Heavy Ion Fusion Science
Virtual National Laboratory

*This work was performed under the auspices of the US Department of Energy by LLNL under Contract DE-AC52-07NA27344 and by LBNL under Contract DE-AC02-05CH11231.

“Future generations will need fusion” - Dr Richard Post

fusion researcher was named one of the Worst Jobs in Science by *Popular Science*



Fusion Researcher

Edwin Fotheringham

“Future generations will need fusion. No other energy source compares with this,” says 85-year-old Lawrence Livermore National Lab physicist Richard Post. Yet fusion is meaningless as a power source until the reaction of combining atomic nuclei produces more energy than scientists put in to get it going. Post has devoted 50 years of his life to achieving this critical point, called breakeven, and it’s still up to 20 years away—“and always will be,” joke many scientists. Post and his colleagues compare themselves wistfully to the stoneworkers of medieval cathedrals: “They had a certain faith that they were making something crucial for future generations,” Post says—a faith that allowed them to grunt and sweat toward a fruition that would come only long after they were gone.

from Popular Science, 26 January 2009

What's the Heavy Ion Fusion Science Virtual National Laboratory?

HIFS-VNL is a consortium formed in 1996 by LBNL, LLNL, and PPPL

LLBL

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Jin-Young Jung	Ed Lee	Steve Lidia	Pavel Ni	Lou Reginato
Prabir Roy	Peter Seidl	Derek Shuman	Jean-Luc Vay	Will Waldron

LLNL

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Ralph Moir	Art Molvik	Dick More	John Perkins	Bill Sharp

PPPL

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Hong Qin	Ed Startsev			

plus collaborators around the world...

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Outline

motivation

- Why worry about energy? Why fusion? Why not renewables or fission?

a fusion primer

- What's fusion? What's stopping us?
- How can we get energy from fusion? gravity vs magnetic fields vs inertia

rudiments of heavy-ion fusion

- What are the advantages of inertial fusion?
- What are the driver options? Lasers vs ions vs electrons
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US inertial fusion research

- What's the direction of the US program?
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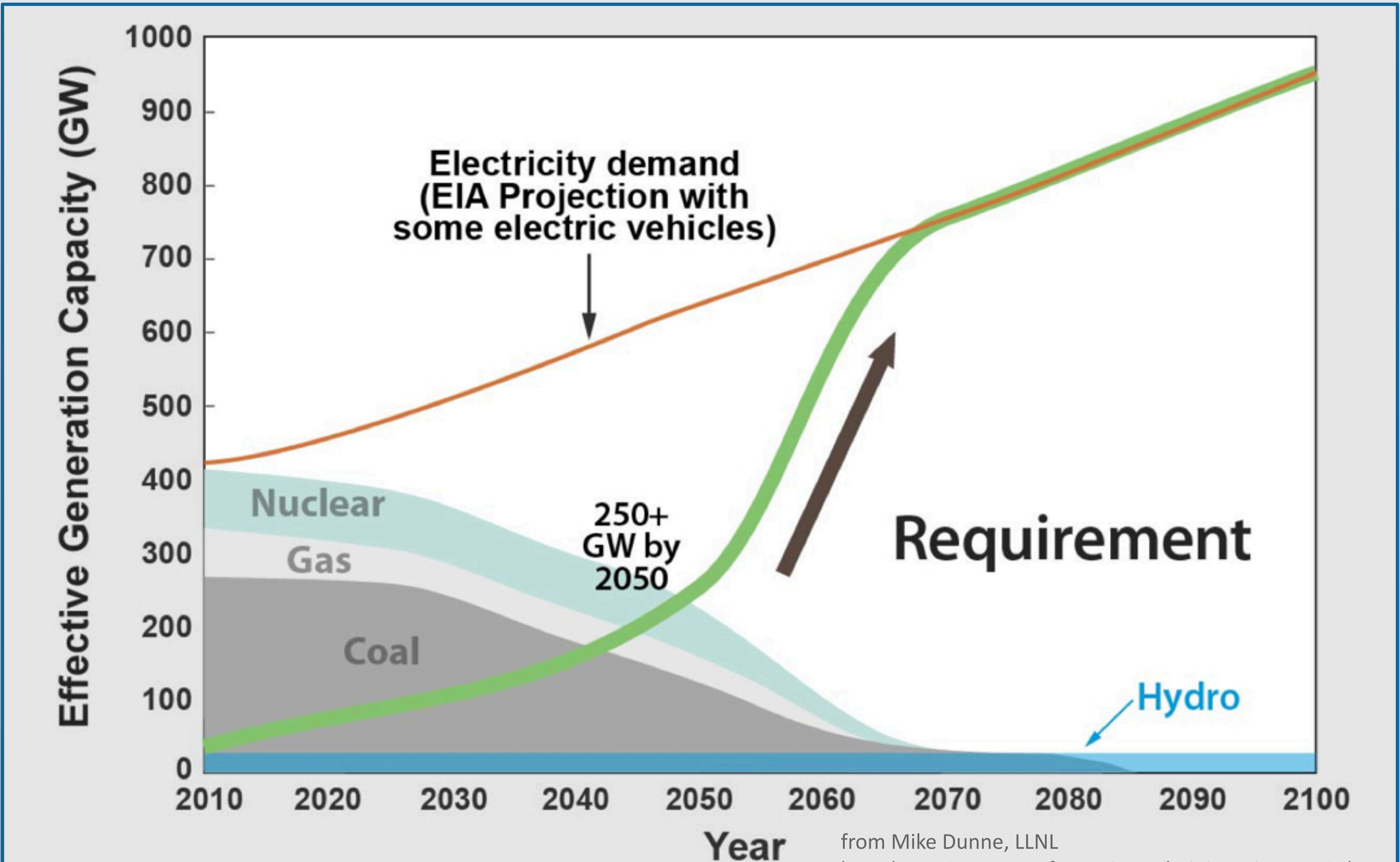
- What are we doing now? Introduction to NDCX-II

future research directions

Should we be concerned about energy?

retirement of US power plants will lead to a large demand for new sources by 2050

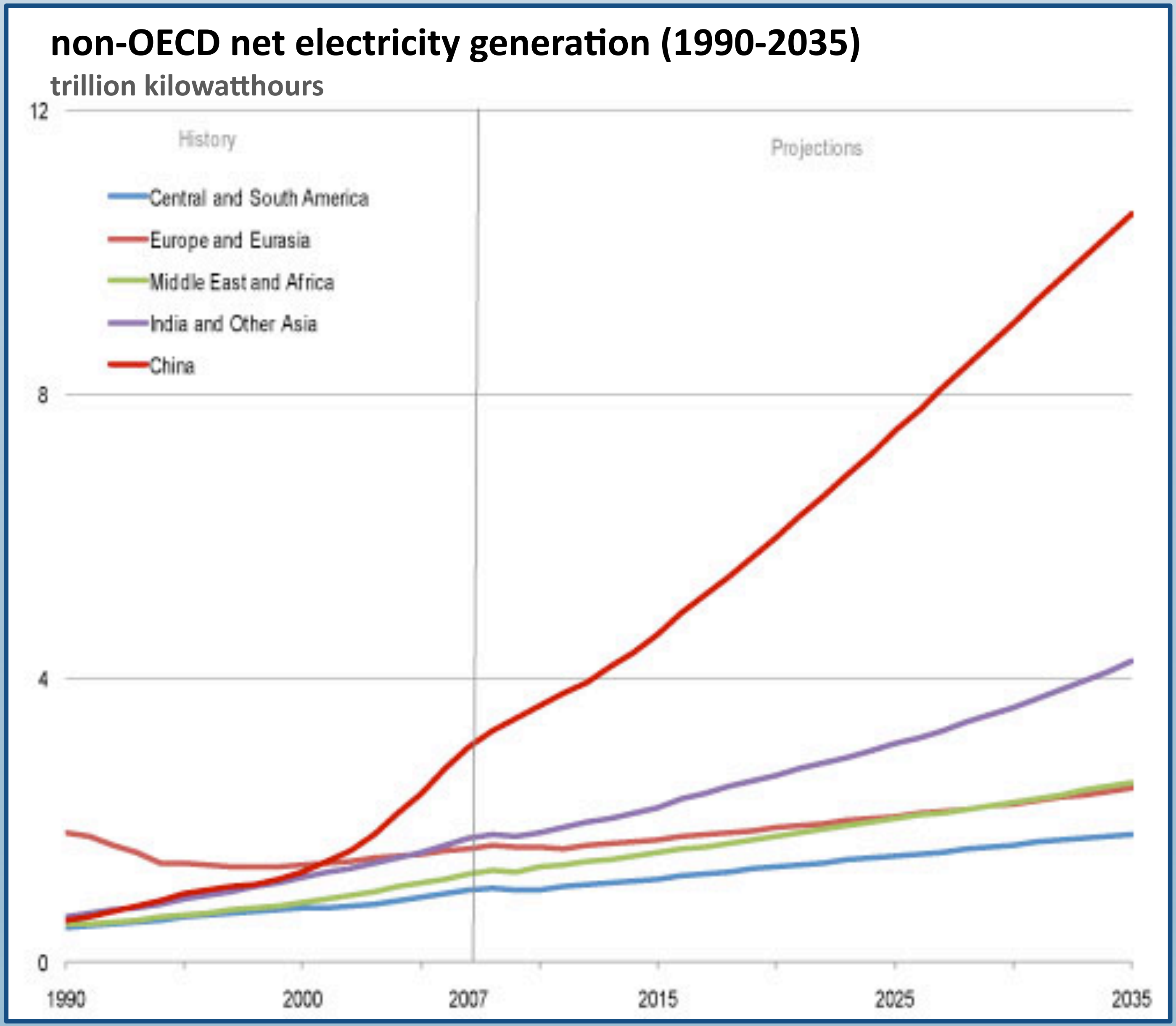


from Mike Dunne, LLNL
based on US Energy Information Administration 2009 data

How about other countries?

rapid modernization is creating huge energy demands in India and China

- China overtook the US in 2009 as the largest oil consumer
- China and India are the two fastest growing automobile markets
- electricity generation in China is projected to triple in the next twenty-five years



from US Energy Information Administration 2009 data

Fossil fuels are abundant but pose environmental problems

coal is the cheapest and most plentiful fossil fuel but...

- sulfur and nitrogen impurities from coal lead to “acid rain”
- particulates can cause severe air pollution near power plants
- equipment to trap or sequester pollutants is costly
- mining is messy

oil is the principal fuel for transportation but...

- use is skyrocketing is developing countries like China and India
- worldwide production is predicted to peak by 2020
- increasing demand and limited supplies may increase price
- uneven distribution of known reserves poses political problems

natural gas is the cleanest burning fossil fuel

- new reserves continue to exceed use but...
- the largest reserves are in the Middle East

and there’s that carbon dioxide...

What about global warming?

fact: burning fossil fuels has substantially increased atmospheric CO_2

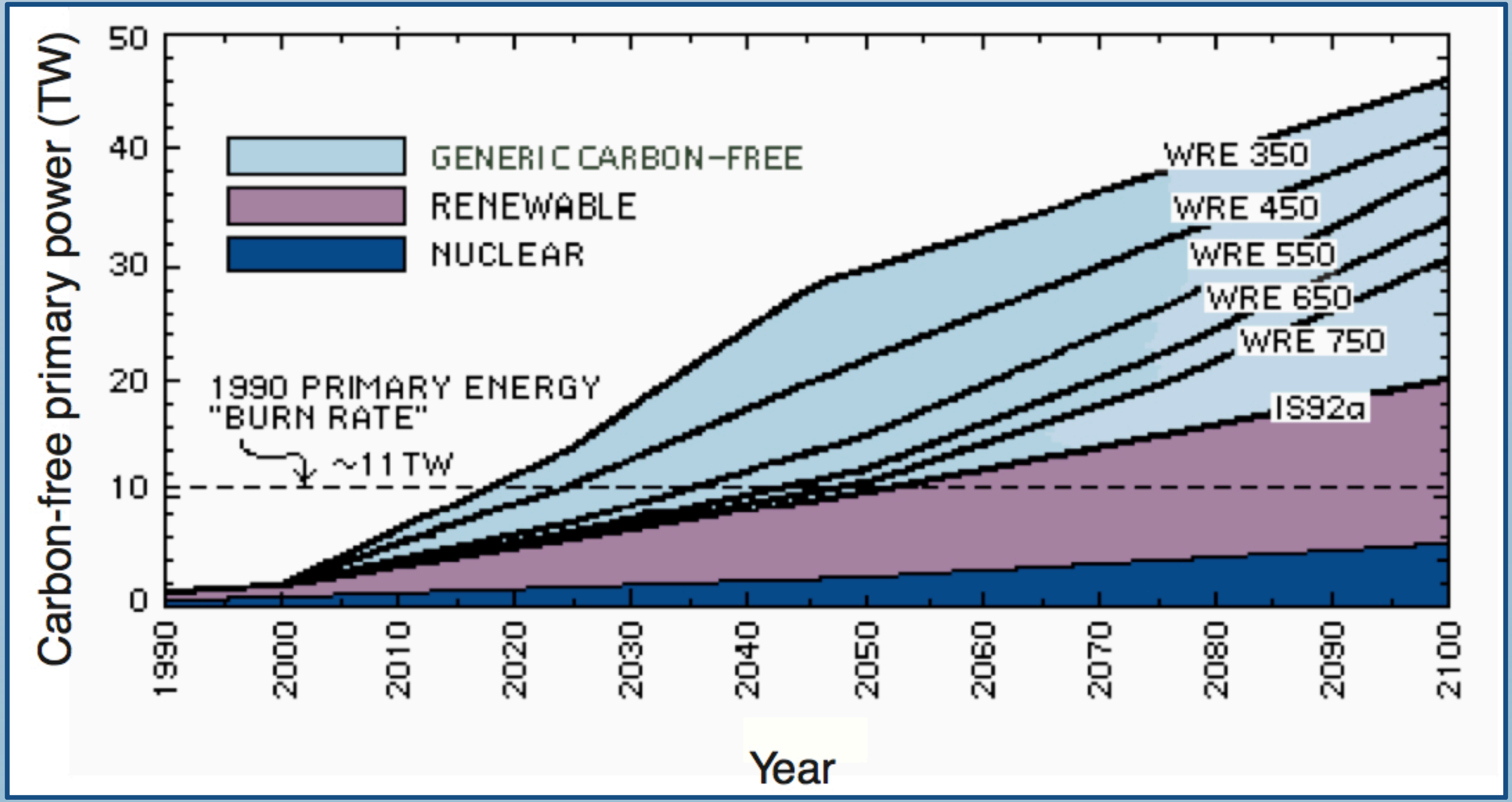
fact: CO_2 traps some infrared light radiated from earth's surface ("greenhouse effect")

fact: evidence is accumulating for a long-term increase in earth's temperature

fact: climate modeling is too complicated to reliably predict future changes

non-apocalyptic inferences

- **carbon-free energy sources should be aggressively developed**
- **these new energy sources should replace fossil-fuel ones as they are retired**



from M I Hoffert et al., *Nature* **385**, 881 (1998)

Renewables are like to remain niche sources

solar energy is abundant but...

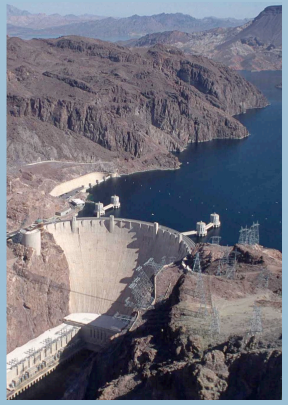
- diffuse, averaging 680 W/m^2
- has regular daily and seasonal fluctuations
- is currently expensive (solar panels are \$4000/kW)
- commercial conversion technology is inefficient (~15%)

wind energy is growing rapidly but...

- usable sites are spotty
- has unpredictable fluctuations
- is currently expensive (wind turbines are \$4000/kW for multi-MW units)
- poses noise problems and can endanger birds and bats

geothermal energy is clean and reliable but...

- usable sites are scarce



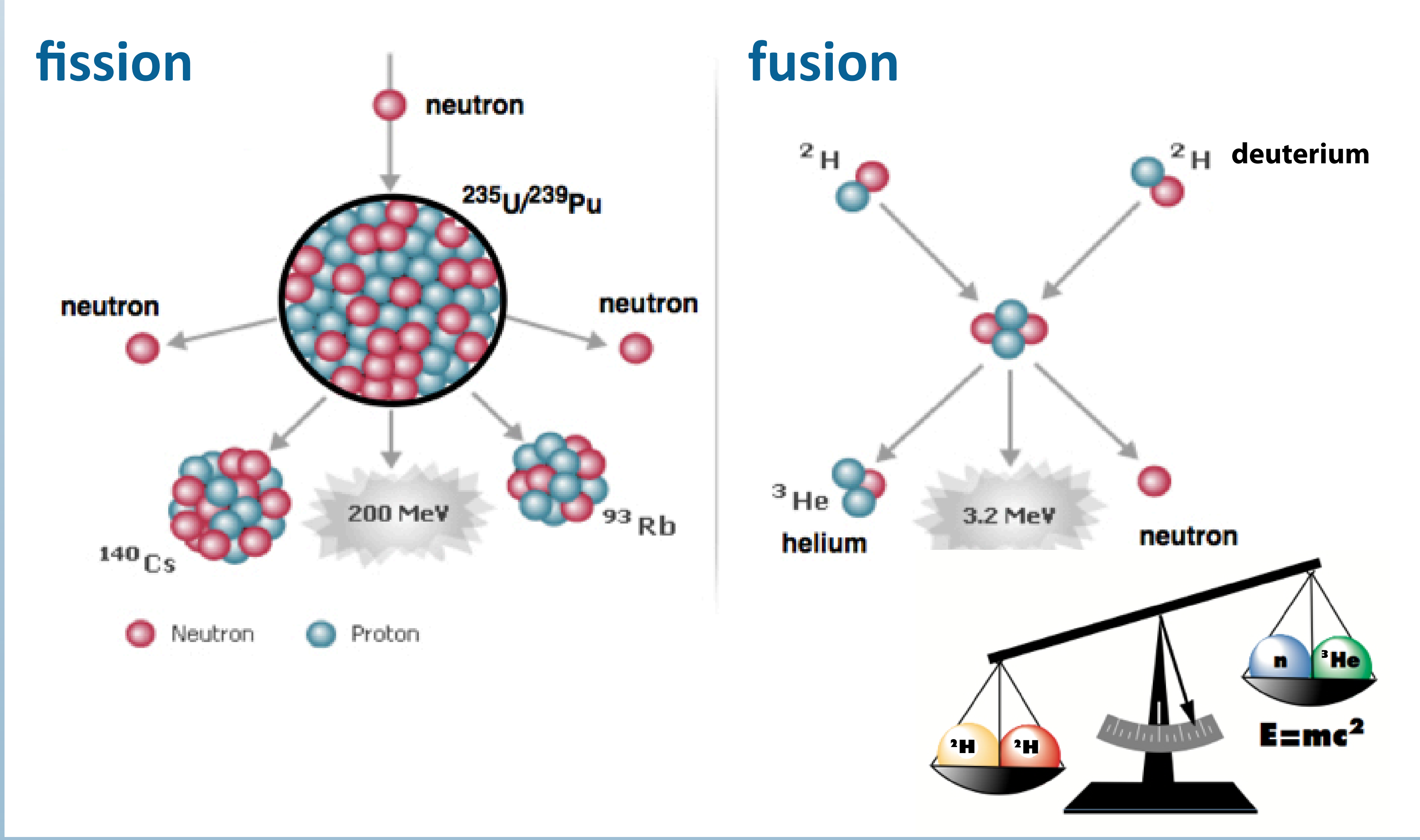
hydroelectric energy is reliable but...

- best sites are already used
- dams disturb nearby habitats

fission and fusion both produce energy from nuclear forces

some mass is lost when large nuclei split or small ones merge

- this mass converted to energy according to Einstein's equation $E = mc^2$
- energy escapes as kinetic energy of particles or nuclei, or as gamma rays



So why is nuclear energy interesting?

carbon-free!

plentiful

- a cubic-foot of sea water contains enough deuterium to equal 30 gallons of gasoline
- uranium reserves, properly used, could last for centuries

versatile

- nuclear energy can produce electricity, hydrogen, synthetic fuels, desalinated water, ...

highly concentrated

- annual fuel requirement for a 1000 MW_e power plant is

2.1×10^6 metric tons of coal - about 21 000 rail cars

10^7 barrels of oil - about 10 super tankers

30 metric tons of UO_2 - about one rail car

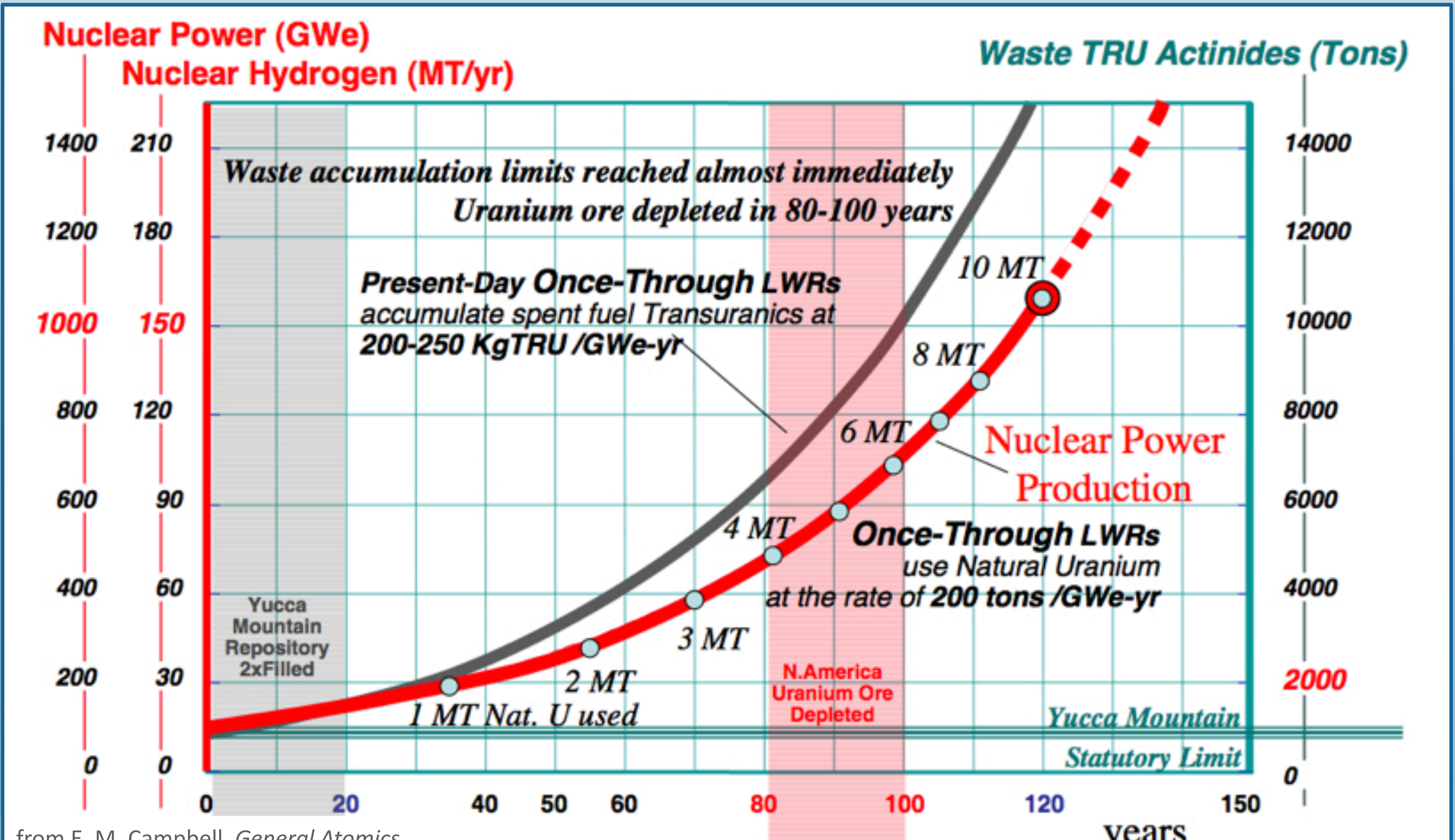
0.6 metric tons of deuterium - one pickup truck

a digression on fission

conventional light-water reactors (LWRs) seem a poor choice for future power plants

- less than 10% of fissionable material is consumed before fuel rods are poisoned
- reliance on LWRs would exhaust uranium reserves and waste storage sites before 2100

pebble-bed breeders or liquid-fluoride thorium reactors seem better options



from E. M. Campbell, *General Atomics*

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What are the candidate fusion fuels?

the original - primary reaction in the sun

$p^+ + p^+ \rightarrow D + e^+ + \nu_e$ + 0.43 MeV ~1 keV (10^7 °C) with D = deuterium (^2H)

$e^+ + e^- \rightarrow 2\gamma$ + 1.02 MeV

the easiest

$D + T \rightarrow {}^4He + n$ + 17.6 MeV ~10 keV (10^8 °C) with T = tritium (^3H)

"advanced" fuels

$D + D \rightarrow {}^3He + n$ + 3.3 MeV ~30 keV (3×10^8 °C)

$\rightarrow T + p^+$ + 4.0 MeV

$D + {}^3He \rightarrow {}^4He + p^+$ + 18.4 MeV

"ultimate" fuels

$p + {}^{11}B \rightarrow {}^4He + {}^4He + {}^4He$ + 8.7 MeV ~50 keV (5×10^8 °C)

$p + {}^7Li \rightarrow {}^4He + {}^4He$ + 17.3 MeV

$p + {}^9Be \rightarrow {}^4He + {}^6Li$ + 2.1 MeV

a note on energy units:

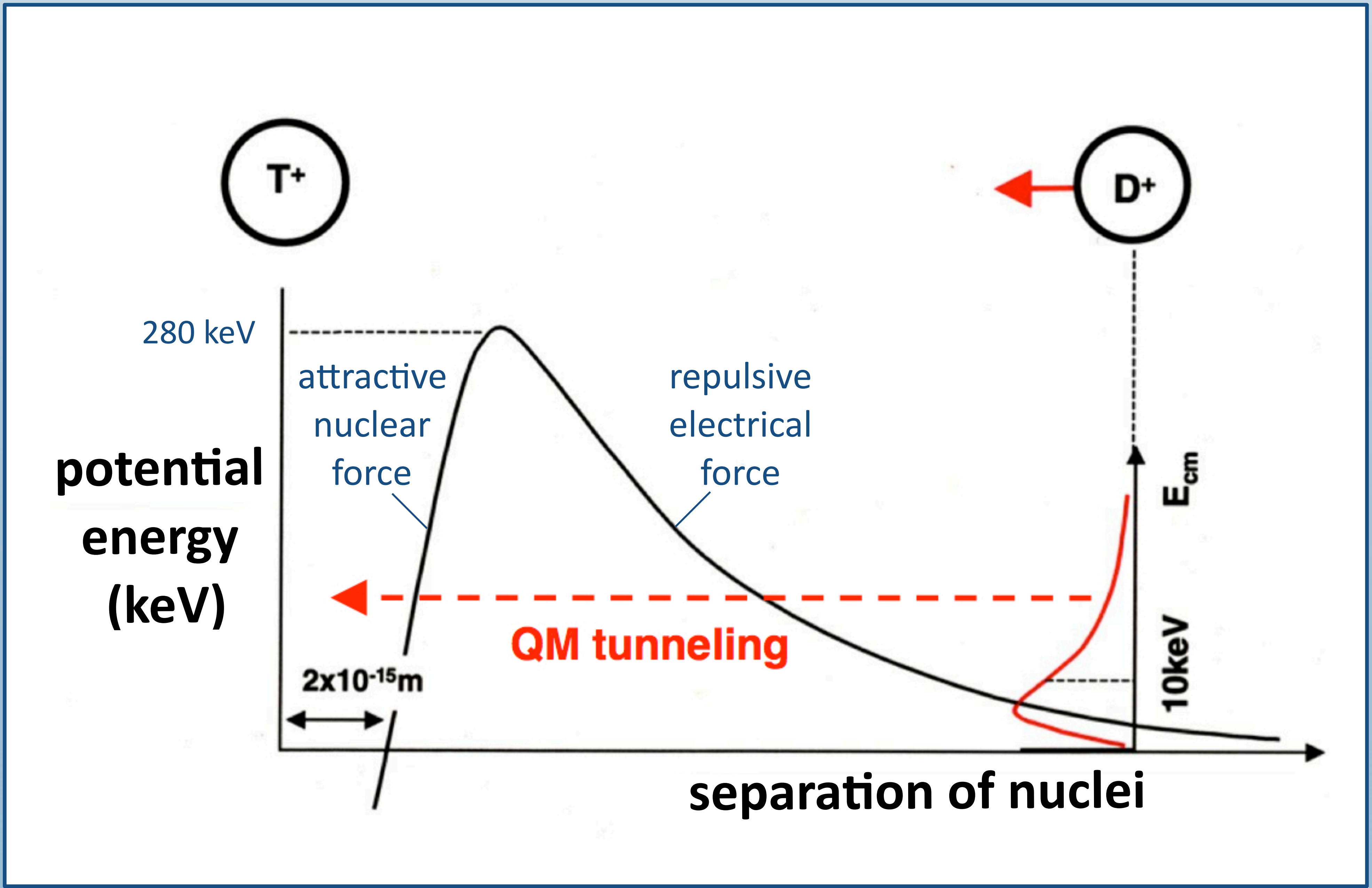
1 eV (electron-volt) = 1.602e-19 Joules . Characteristic of energy changes in *atomic* processes

1 MeV = 1.602e-13 Joules. Characteristic of energy changes in *nuclear* processes

Why has controlled fusion taken sixty years?

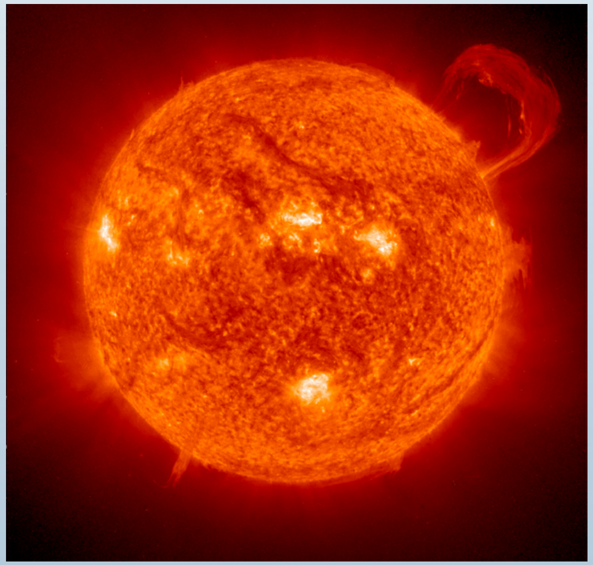
thermonuclear fusion depends on quantum-mechanical tunneling of energetic ions

- **probability only becomes appreciable for very energetic ions (> 10 keV or 10^8 °C)**
- **electrons are dissociated from nuclei at this temperature, making a Maxwellian plasma**
- **holding a D-T plasma together long enough for fusion has proven a major challenge**



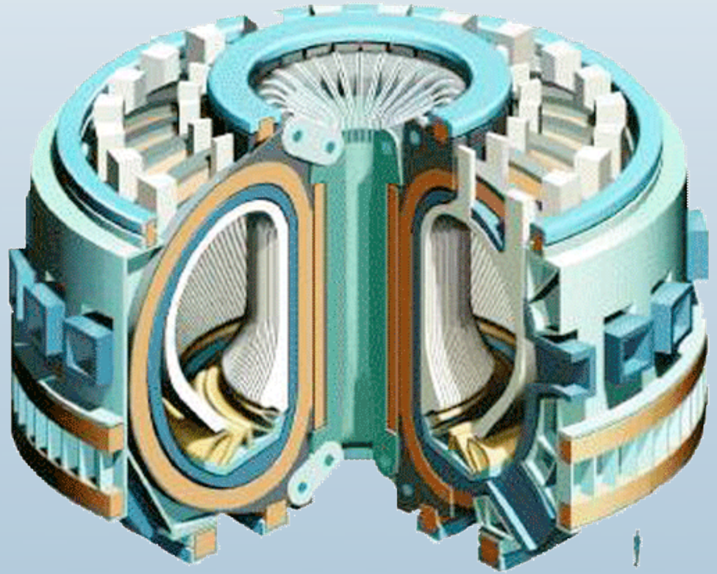
How can we achieve controlled fusion?

three main ways



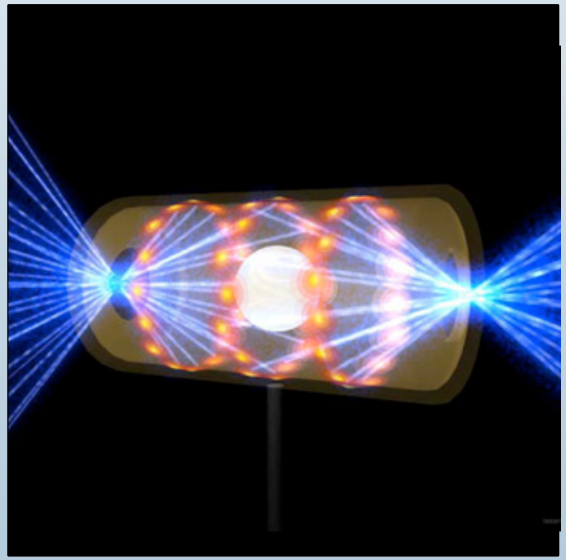
gravitational confinement

"a day without fusion is like a day without sunshine"



magnetic confinement

"...like holding jello together with rubber bands" - Edward Teller



inertial confinement

"A small supernova. Very small" - Ed Moses

	density	temperature	confinement time	status
magnetic	10^{-8} x solid	10 keV	seconds	first test 2020
inertial	10^{3} x solid	10 keV to ignite	10's of picoseconds	first test 2011
gravitational	10^{4} x solid	1 keV	10^{5} years	proven daily

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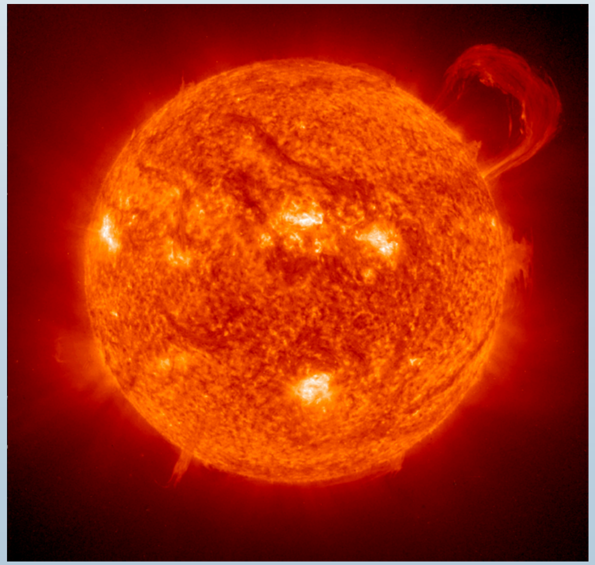

gravitational confinement

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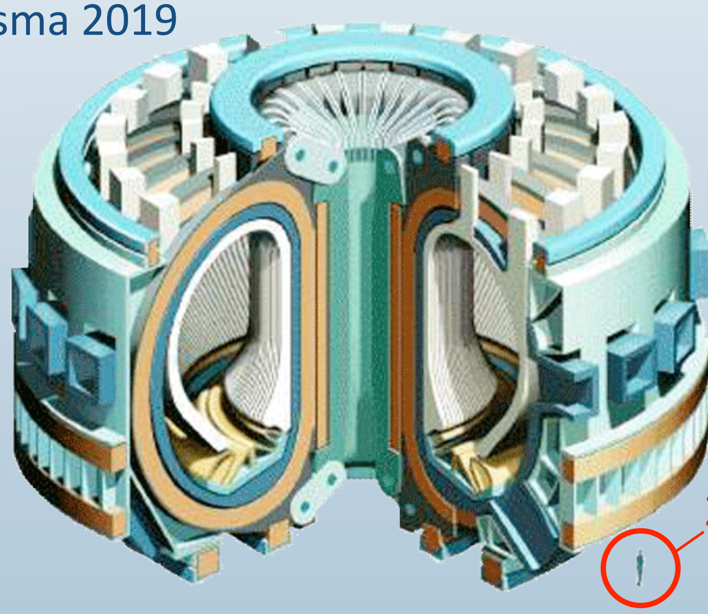
International Tokamak Experimental Reactor (ITER) being built in Cadarache, France
first plasma 2019



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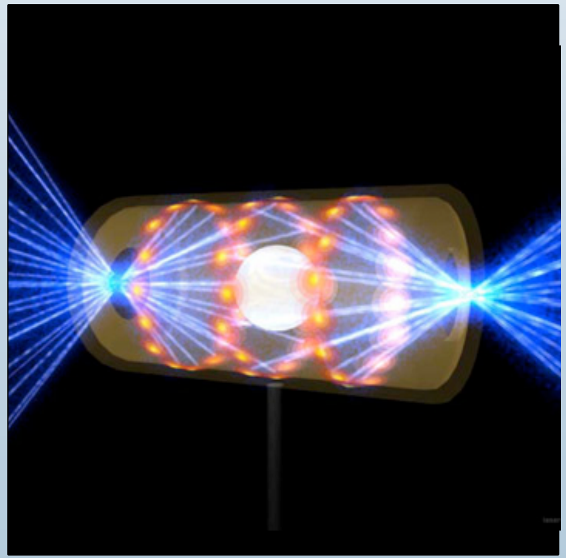

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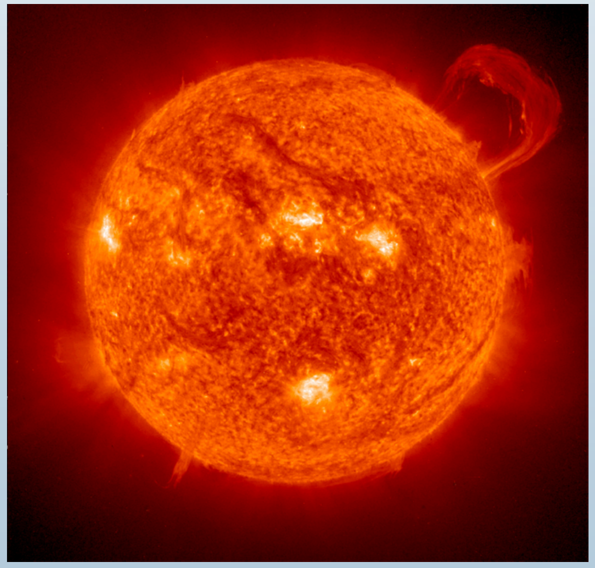

gravitational
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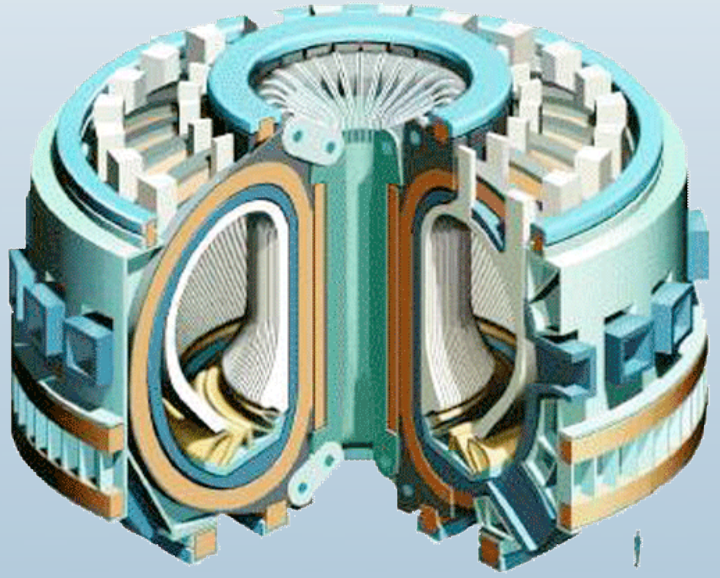

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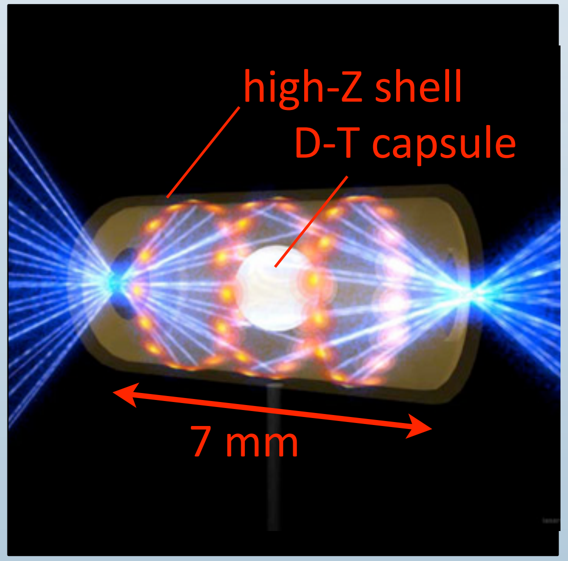
National Ignition Facility (NIF)
completed 2009 in Livermore, CA
2.2 MJ in 192 beams



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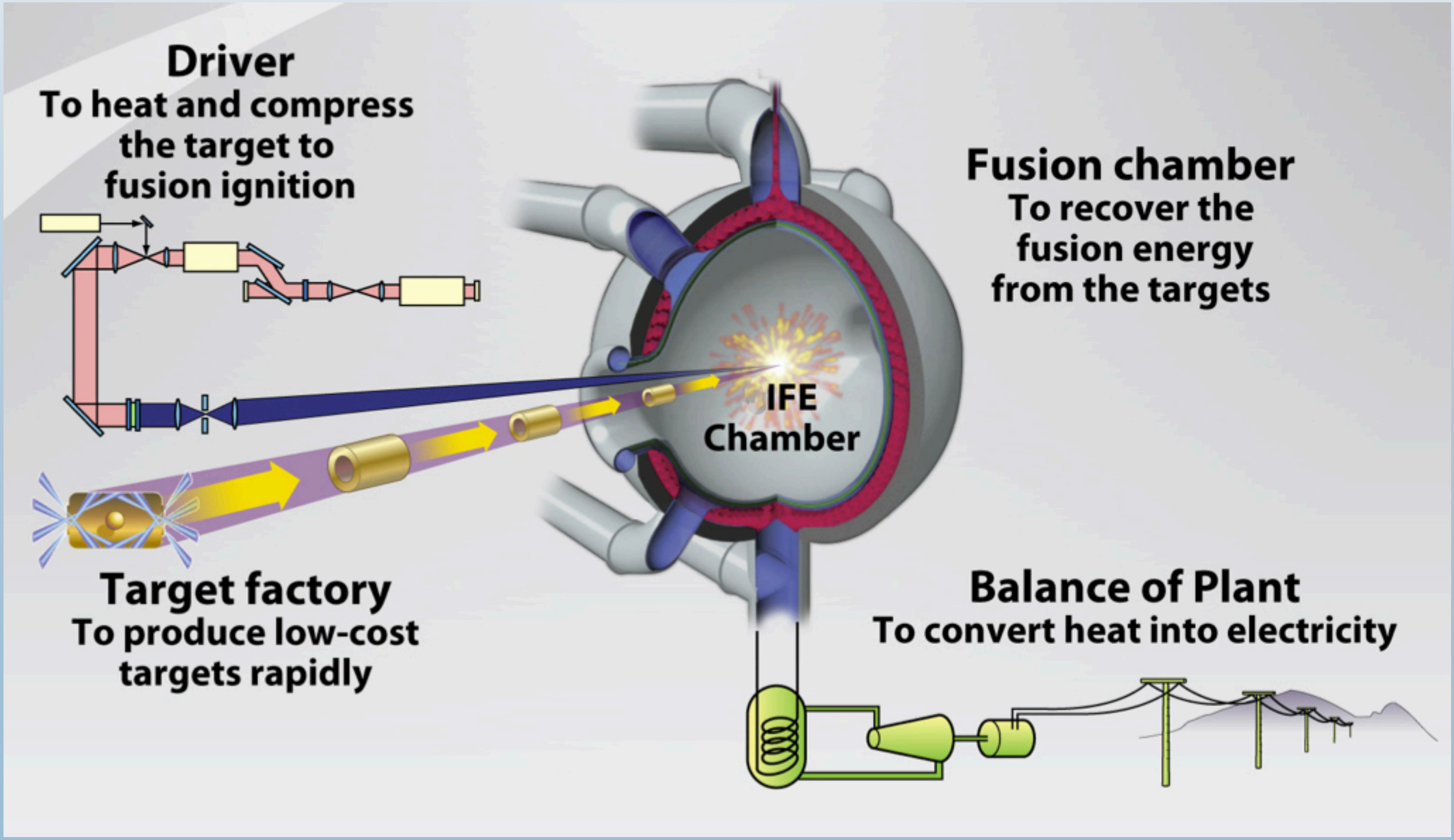
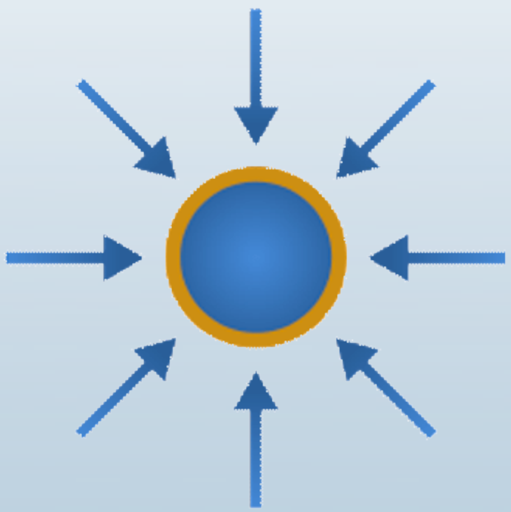
What's needed for an inertial fusion energy power plant?

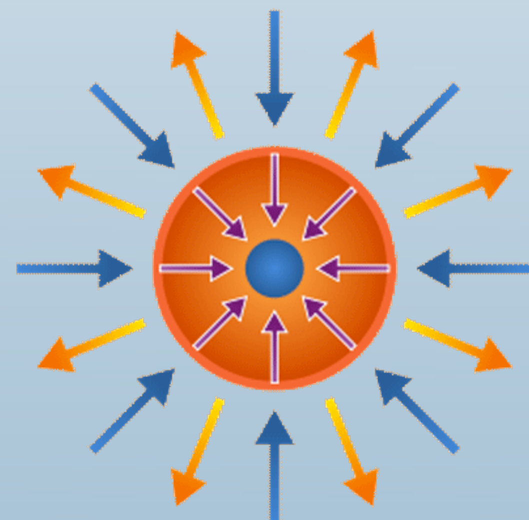
subsystems are highly separable



What goes on in the target?

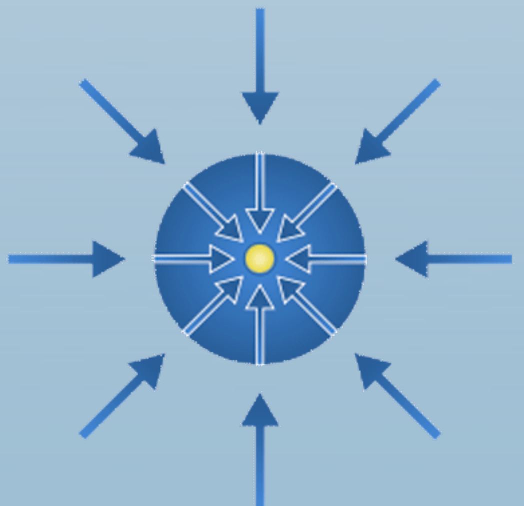


input energy quickly heats surface of fuel capsule



fuel is compressed by rocket-like blowoff of hot surface material

compressed fuel core ("hotspot") reaches density and temperature needed for ignition

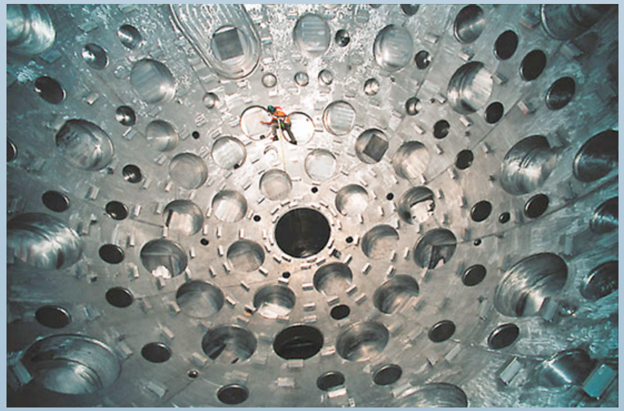


thermonuclear burn spreads quickly through compressed fuel

What are the IFE options?

driver can be anything that delivers concentrated energy (1 - 10 MJ in 10 ns)

- photons
- electrons
- light or heavy ions
- Buckyballs



chamber must protect the wall from blast

- dry walls of neutron-resistant material
- "wetted" walls with a layer of liquid lithium
- "thick-liquid" walls of molten salt

target must convert drive energy into symmetrical compression of D-T capsule

- complicated physics
- "indirect - drive"
- "direct-drive"
- "fast-ignition"

options galore

Why should we be interested in inertial fusion?

safety

- negligible stored energy
- no fissile materials so no proliferation issues
- wastes can qualify for shallow burial (Class-C)

simplicity

- much simpler reactor chamber than a tokamak
- fusion driver is separate from the reactor chamber
- use of thick-liquid walls can ensure long lifetime for first wall

versatility

- many options for driver, chamber, and target

“If you’re so smart, why aren’t you rich?”

worldwide energy will become a $70-trillion industry by 2100 with

- a huge increase in per capita energy use in developing countries
- a total demand that doubles by 2050 and triples by 2100
- a requirement for carbon-free fuels

fusion will have a place in the energy mix *only* if it develops a competitive product

- reliable
- non-polluting
- long power-plant lifetime
- cost competitive with fission and renewables

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future research directions

If laser fusion is expected soon, why bother about heavy-ion fusion?

repetition rate

- NIF can manage 1-2 shots per day
    - a power plat needs 5-10 shots per second

efficiency

- NIF lasers are less than 1% efficient, and recent high-repetition lasers get 15-20%
    - induction accelerators for ions are about 40%

robust final optics

- laser final optics are directly exposed to target blast
    - focusing magnets for ions do not intercept the line-of-sight from the target

thick-liquid walls

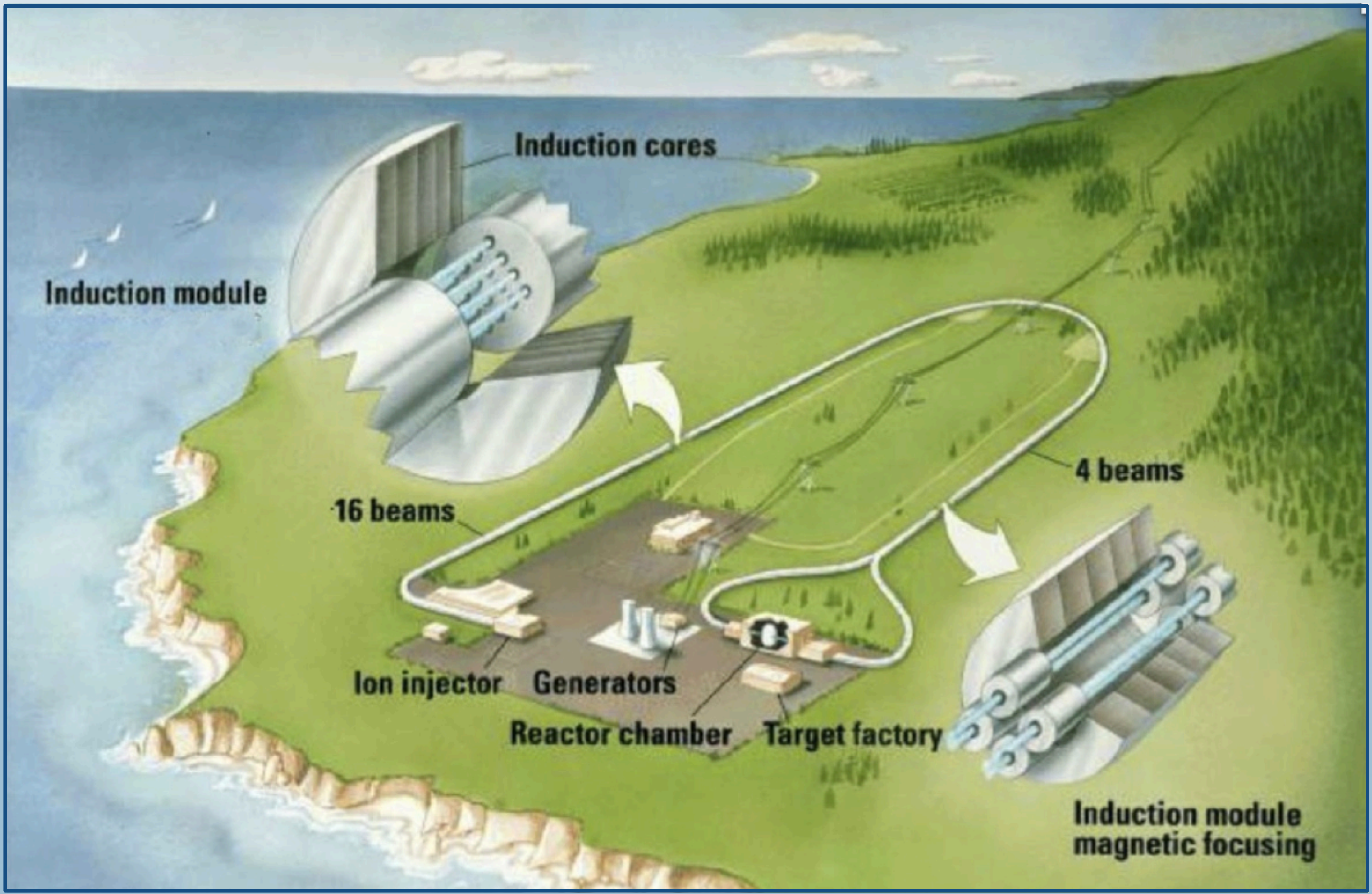
- laser power-plant concepts require periodic replacement of the chamber inner wall
    - heavy-ion power-plant concepts use molten Fl-Li-Be salt to absorb blast

multiple chambers

- high-repetition laser are presently limited to less than 20 Hz
    - much-higher induction-accelerator repetition rates may allow use of multiple chambers

Fanciful picture of an HIF power plant...

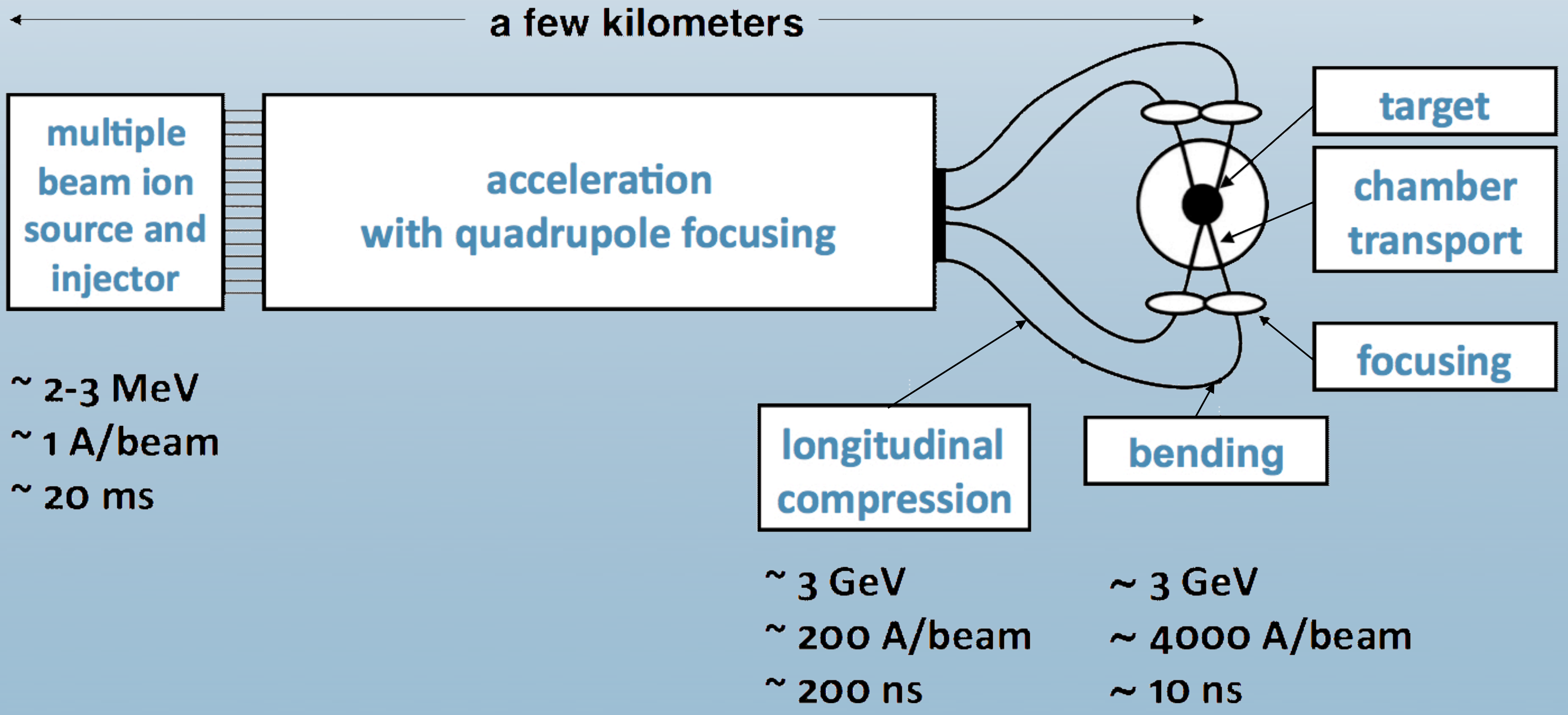
artist's conception from the 1980s



Schematic picture of an HIF power plant

energy-loss scaling $dE/dx \sim Z^{-2}$ enables 10 GeV heavy ions to stop in targets.

- **induction acceleration with superconducting magnets enables high peak beam currents**
- **100's of TW peak power**



How do you design an HIF accelerator”

1 pick a target

- gives the total energy, beam spot size, symmetry requirements

2 pick an ion species

- gives the beam energy and total current

3 choose the method of transverse focusing - solenoids or quadrupoles

- transport limits determine the number and radius of beams

3 design a source to produce the needed charge per beam

4 layout a lattice with required acceleration and beam-end confinement

- beam dynamics is dominated by the space charge of bunches, not their temperature
- beams behave like non-neutral plasmas, so they tend to lengthen

5 work out an acceleration schedule - what fields get applied where

6 *then* start the engineering

This is a different physics regime from conventional accelerators

target requirements for indirect drive

1 - 10 MJ x ~ 10 ns $\Rightarrow$ 0.1 - 1 PW

ion range 0.02 - 0.2 g/cm^2 $\Rightarrow$ 1 - 10 GeV

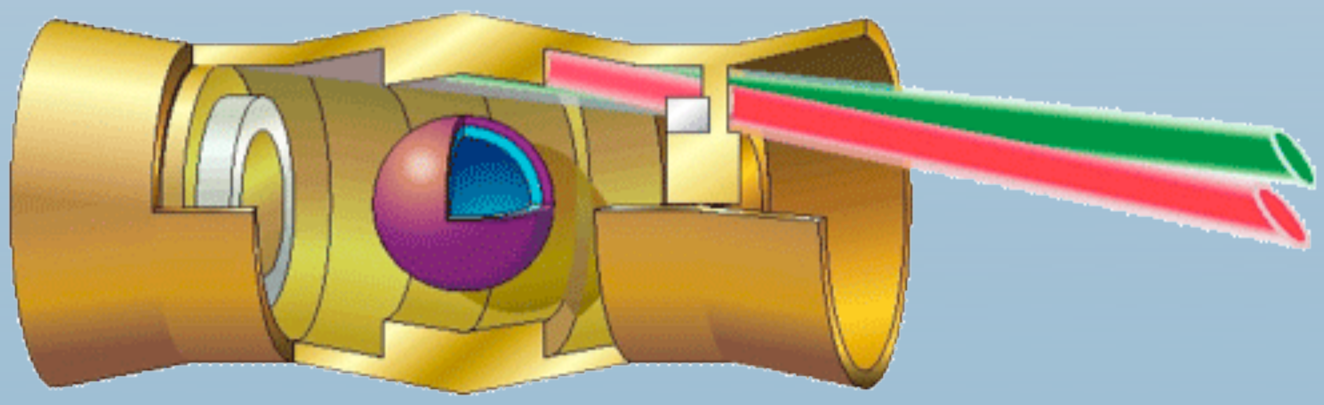
$\Downarrow$

for A ~ 200 $\rightarrow$

~ 10 ^{16} ions

~ 100 beams

1-4 kA / beam



"close-coupled" HIF target
from D. Callahan-Miller and M. Tabak, Phys. Plasmas **7** (2000)

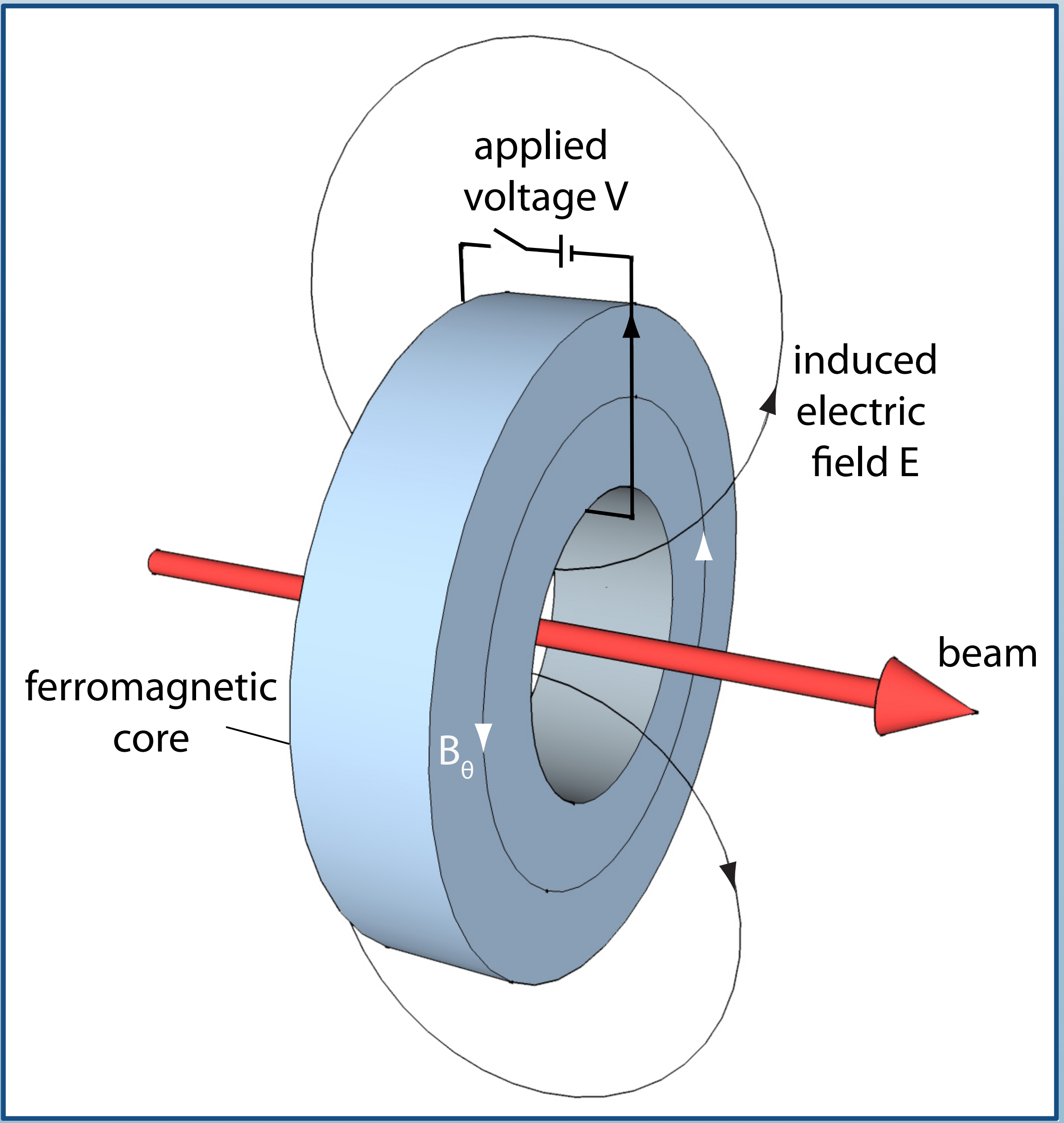
How does an induction accelerator work?

an induction cell works like a transformer

- beam acts as a “single-turn” secondary

changing flux in the ferrite core induces an electric field E_z along the axis

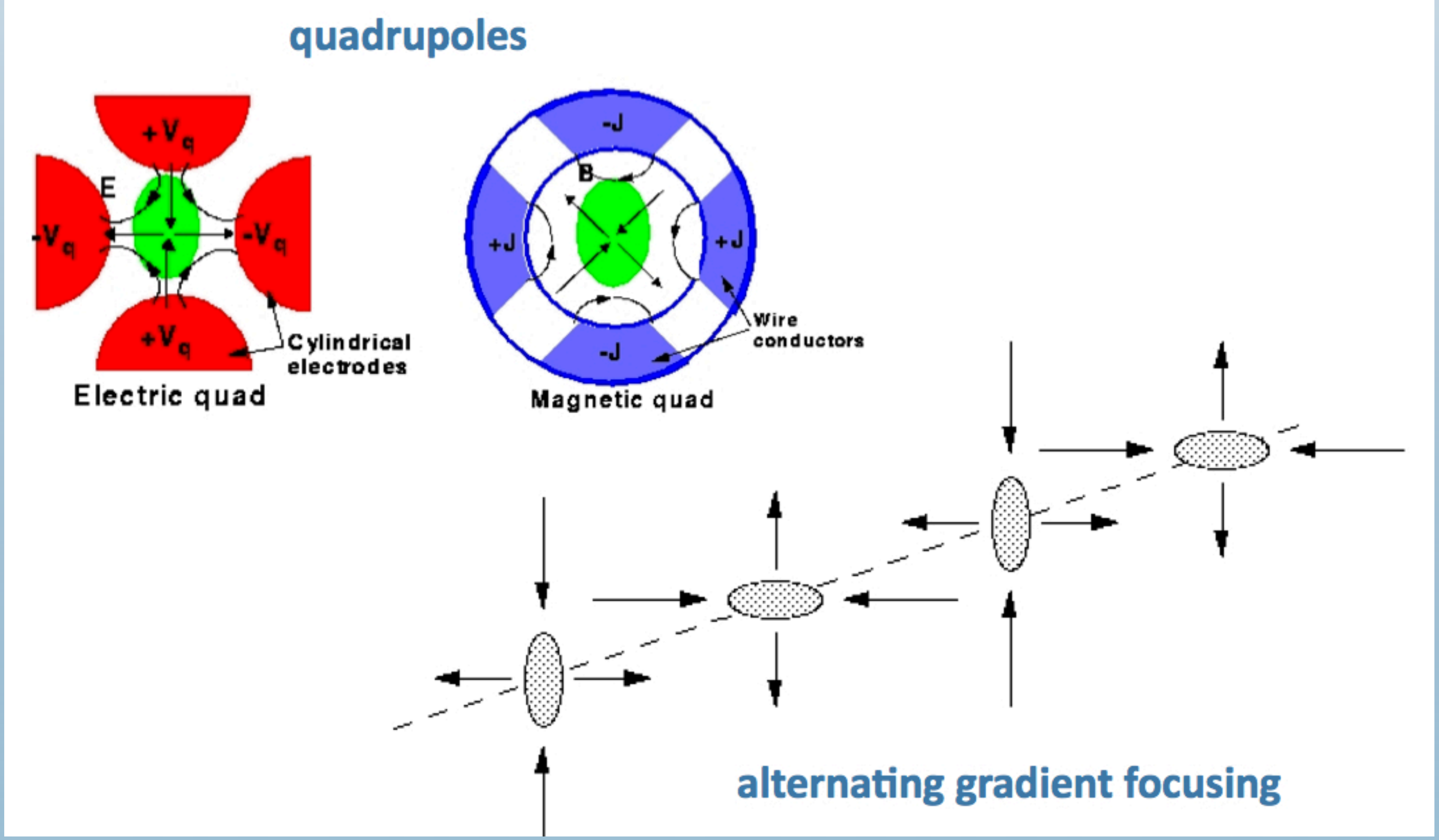
applied voltage waveform determines rate of flux change in the core and hence $E_z(t)$



How does quadrupole focusing work?

quadrupole squeeze the beam alternately in the two transverse directions

- **called "alternate gradient" or "strong" focusing**
- **can use electric or magnetic fields**
- **electric quads work best at low beam velocity. magnetic quads, at high velocity.**



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What are the HIF options?

accelerator

- induction linac, rf linac + storage rings, induction recirculator, dielectric-wall accelerator

transverse focusing

- solenoids, magnetic quadrupoles, electric quadrupoles

final focusing

- neutralized ballistic, vacuum ballistic, self-pinch, two-stage focusing

chamber

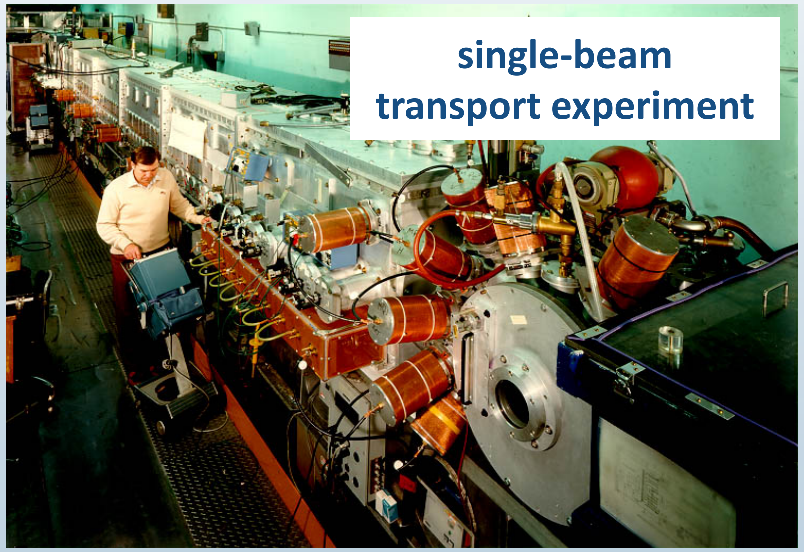
- thick-liquid-protected wall, wetted wall, dry wall + gas fill, granular solid-flow wall

target

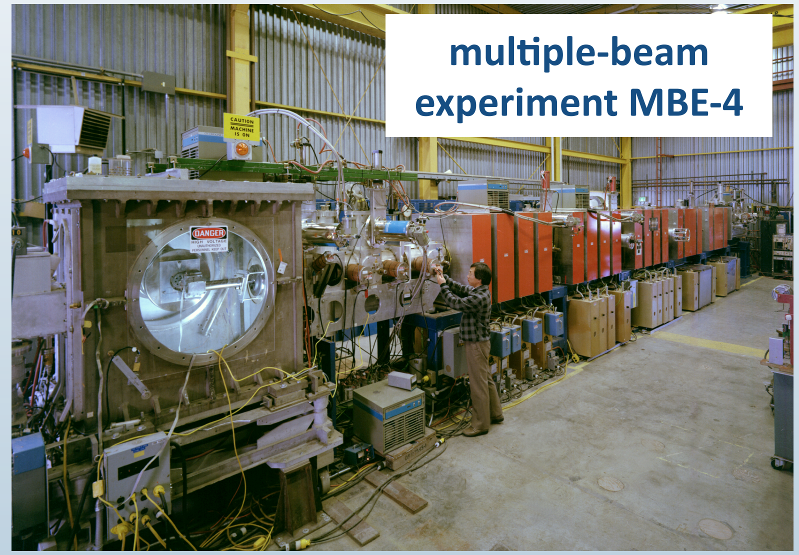
- indirect drive, indirect drive + fast ignition, direct drive, direct drive + shock ignition,....

the US HIF program has focused research on the highlighted options

Past experiments have explored HIF physics with scaled parameters

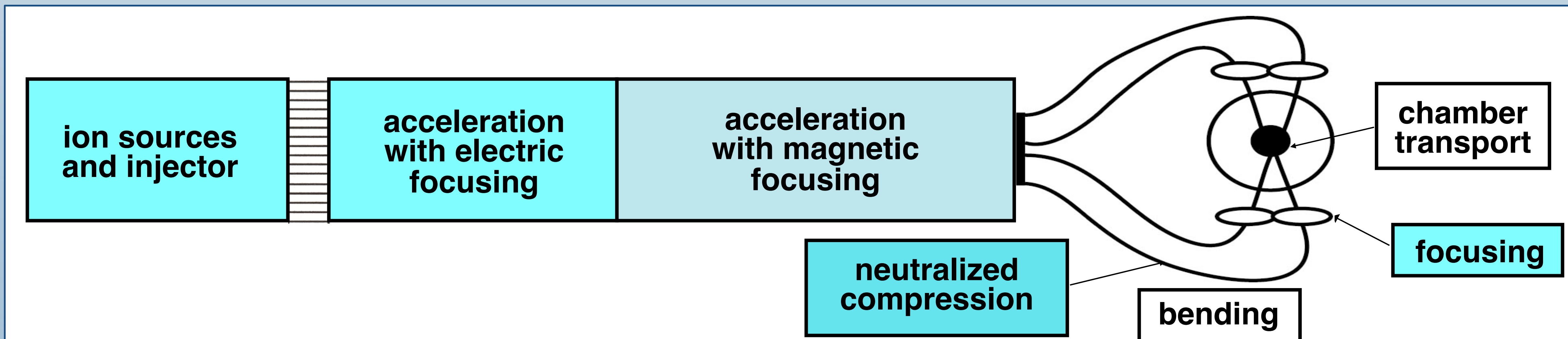


single-beam transport experiment

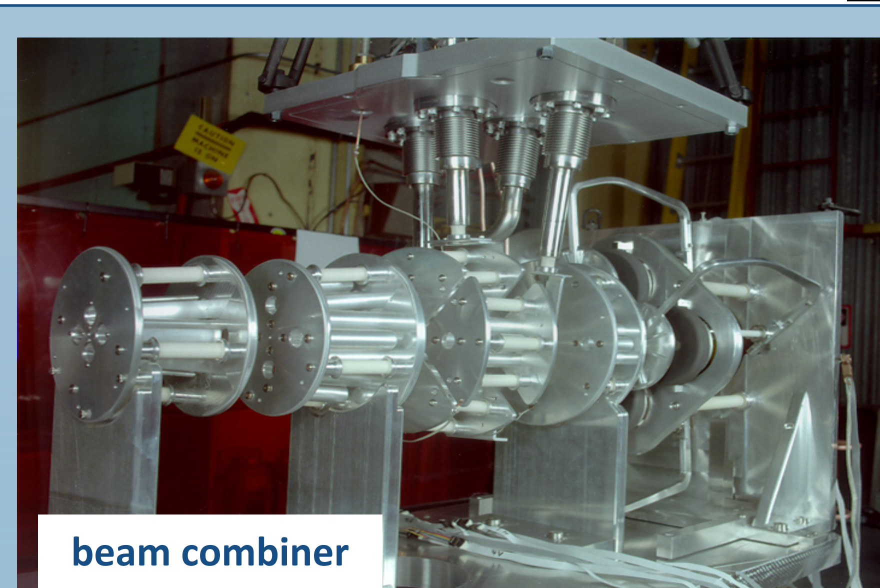


multiple-beam experiment MBE-4

- intense-beam stability
- multiple-beam acceleration
- compression
- beam combining
- final focus
- target tracking
- neutralized compression



2-MeV



beam combiner

scaled final focus

NDCX-I uses neutralized drift compression to routinely achieve current and power amplifications exceeding 50x

injector

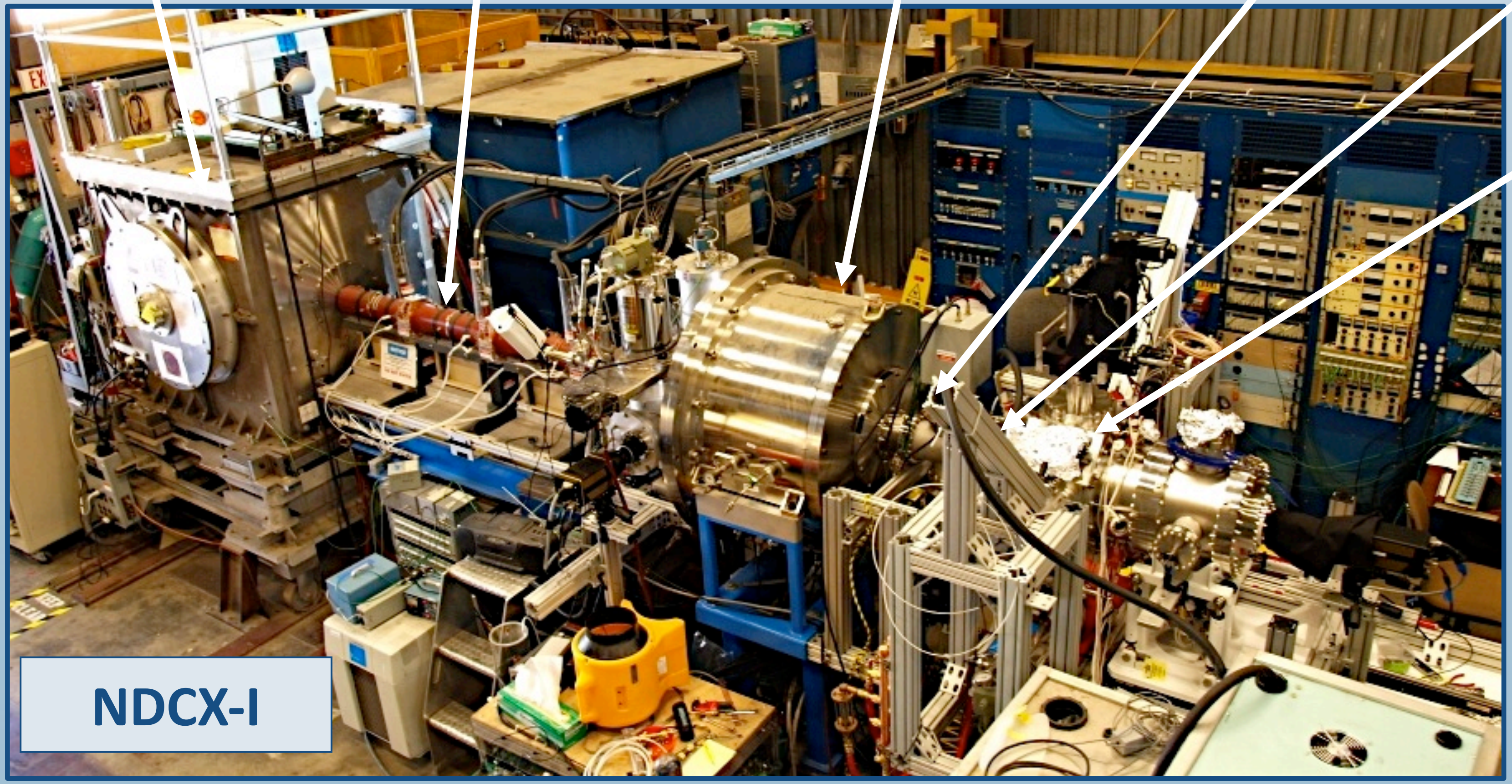
beam-transport solenoids

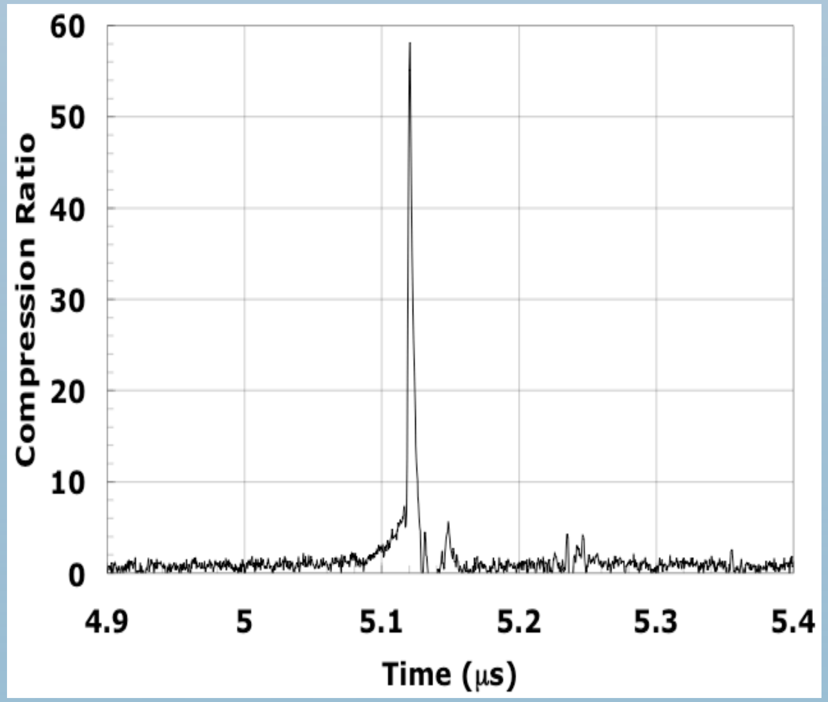
induction bunching module

drift-compression line

final-focus solenoid

target chamber with plasma sources



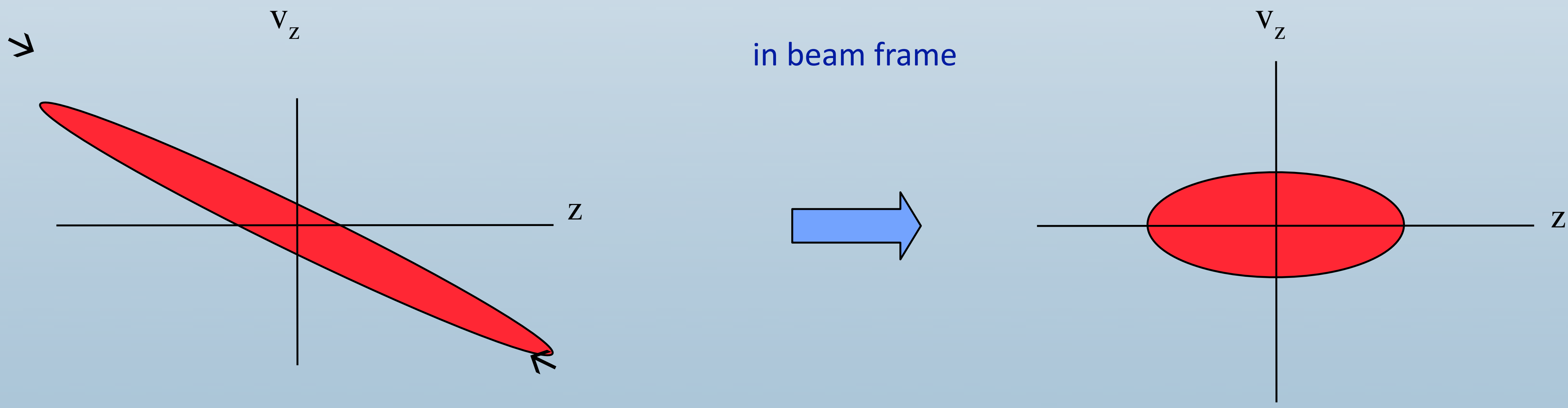


Drift compression is used to shorten an ion bunch

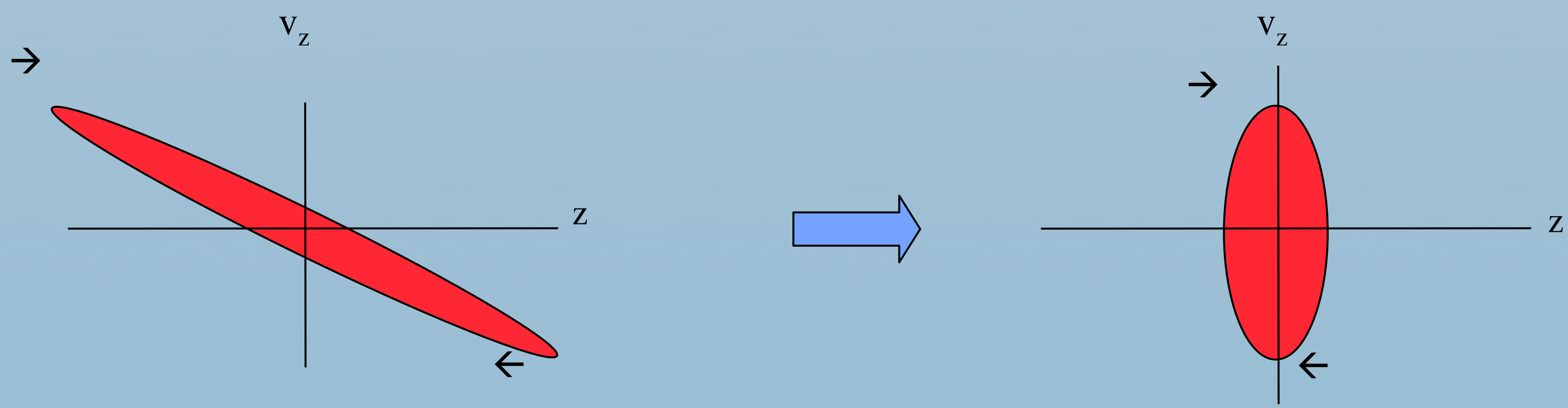
induction cells impart a head-to-tail velocity gradient ("tilt") to the beam

- **the beam shortens as it "drifts" down the beam line**

- **in non-neutral drift compression, the space charge force opposes ("stagnates") the inward flow, leading to a nearly mono-energetic compressed pulse**



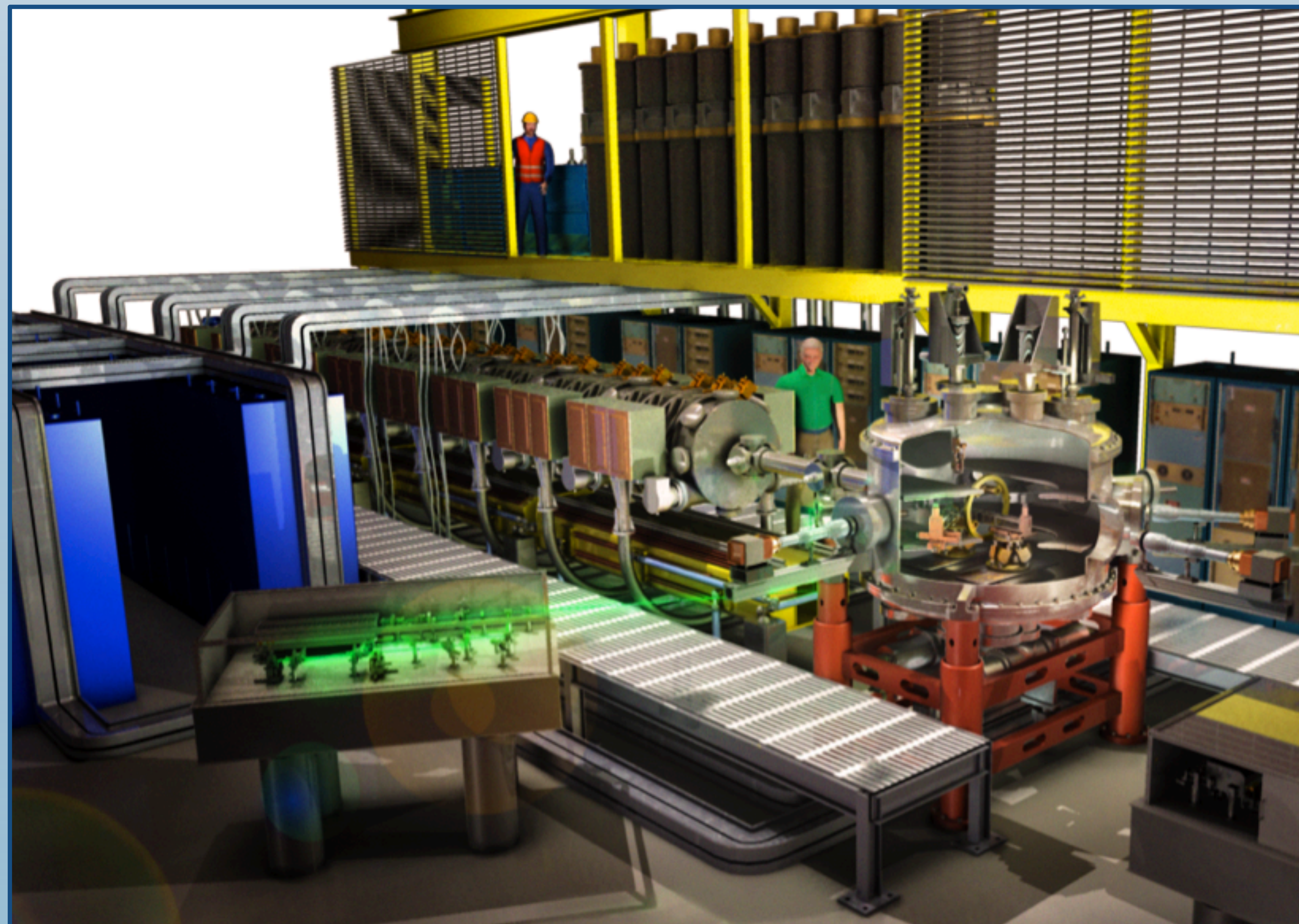
- **in neutralized drift compression, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread**



The NDCX-II project is well underway

DOE Fusion Energy Sciences office approved NDCX-II in 2009.

- $11 M funding was provided via the American Recovery and Reinvestment Act
- construction of the initial configuration began in July 2009
- project completion is due by March 2012
- commissioning will begin in fall 2011
- HEDP target experiments will follow



LLNL gave us 50 induction cells from the ATA electron accelerator

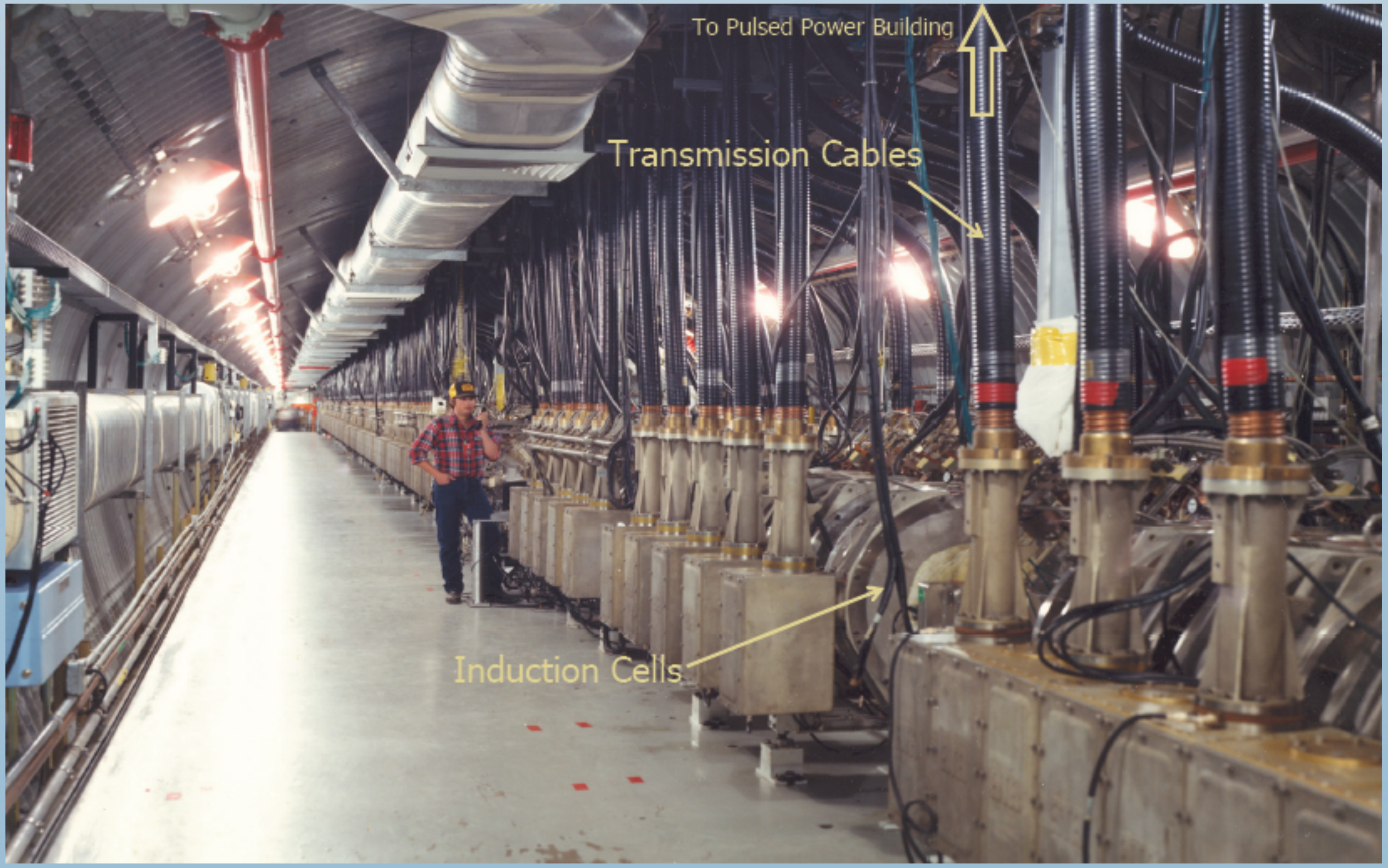
ferrite cores offer 1.4 x 10^{-3} Volt-seconds

Blumlein voltage sources offer 200-250 kV with FWHM duration of 70 ns

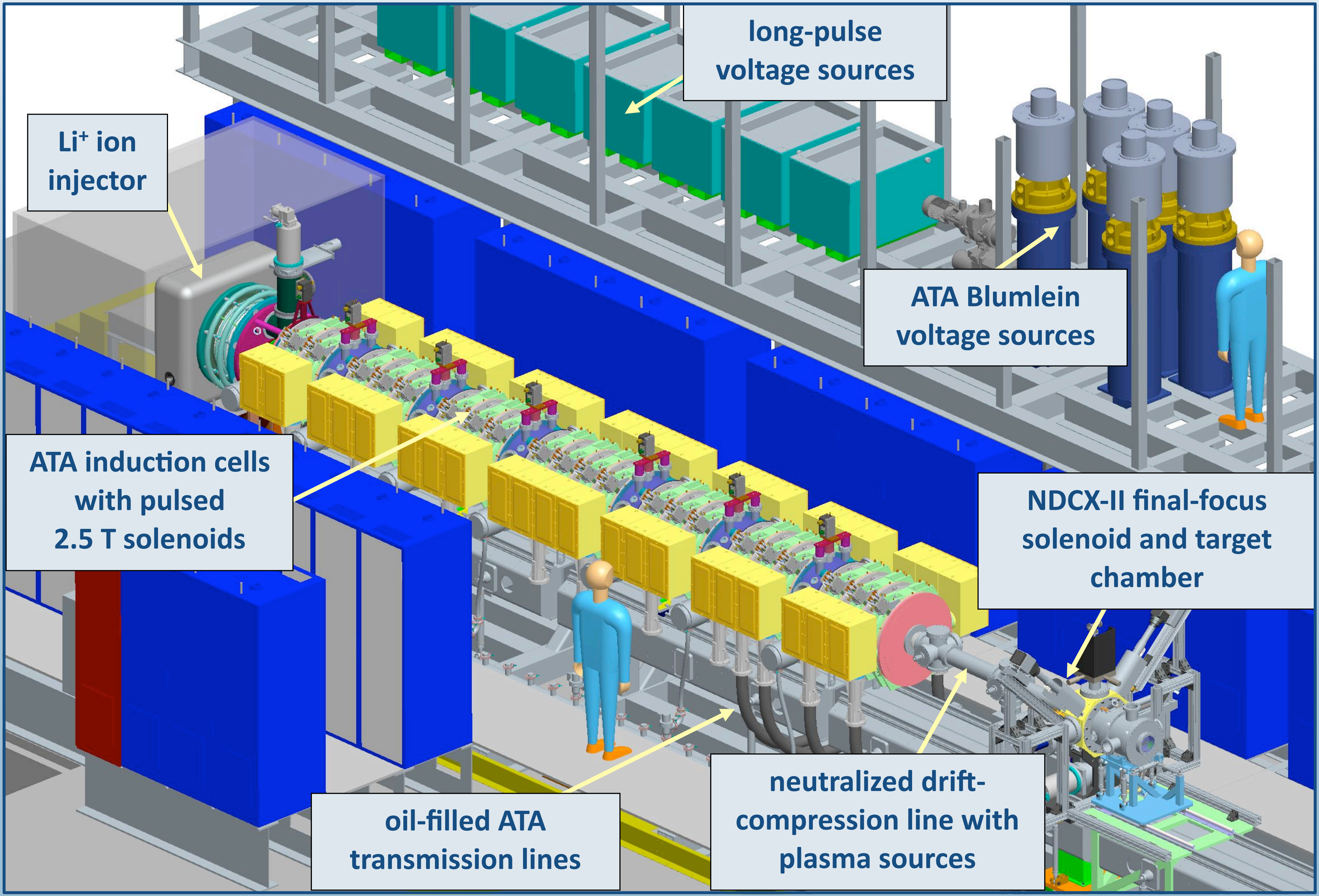
longer beam at front end needs custom voltage sources < 100 kV

ion beam requires stronger (3T) pulsed solenoids and other cell modifications

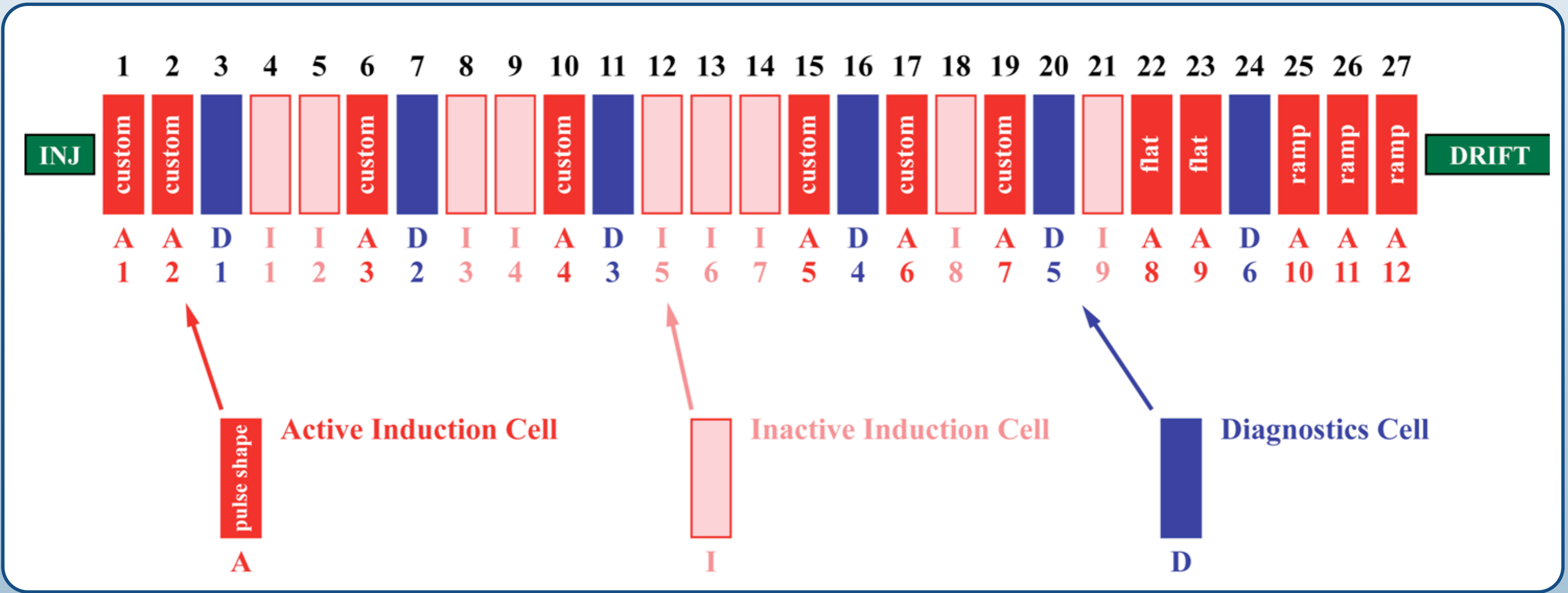
Advanced Test Accelerator (ATA)



12-cell NDCX-II baseline layout



The baseline NDCX-II hardware configuration



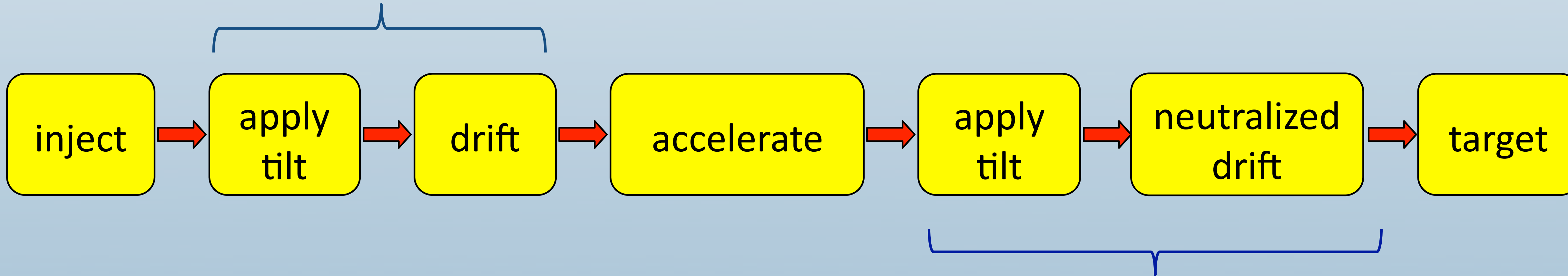
- 27 lattice periods after the injector
- 12 active induction cells
- beam charge ~ 50 nano-Coulombs
- FWHM < 1 ns
- kinetic energy ~ 1.2 MeV

as presented during the April 2010 DOE Project Review

Drift compression is used twice in NDCX-II

initial non-neutral pre-bunching for

- **better use of induction-core Volt-seconds**
- **early use of 70-ns 250-kV Blumlein power supplies from ATA**

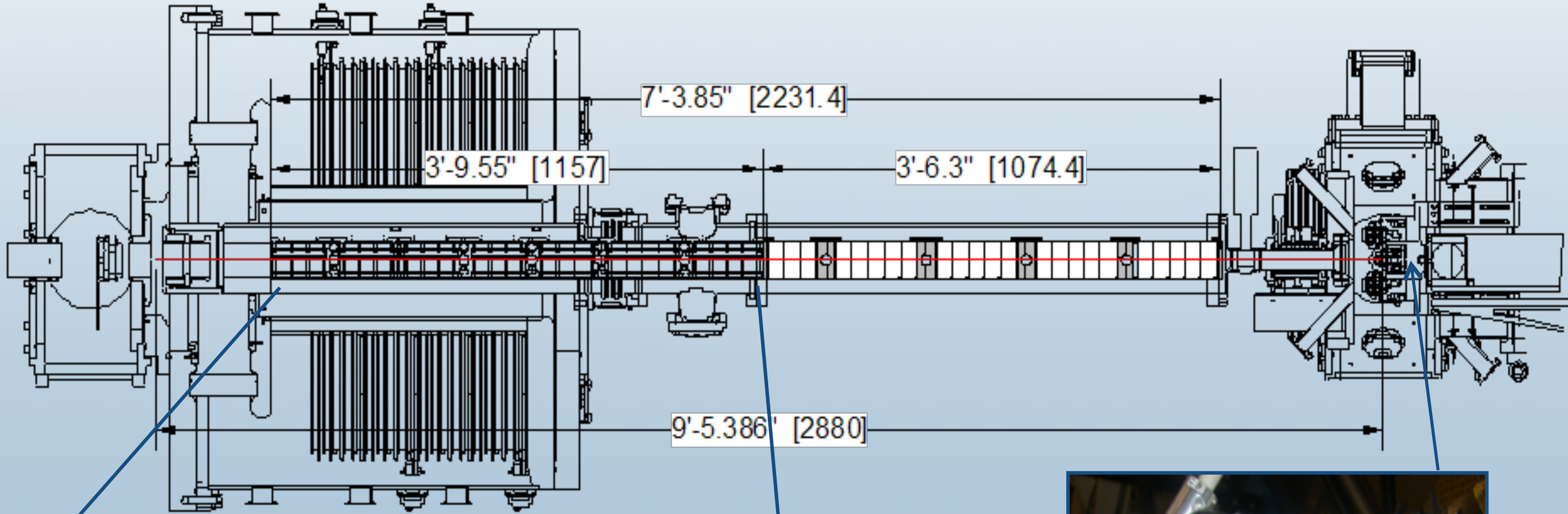


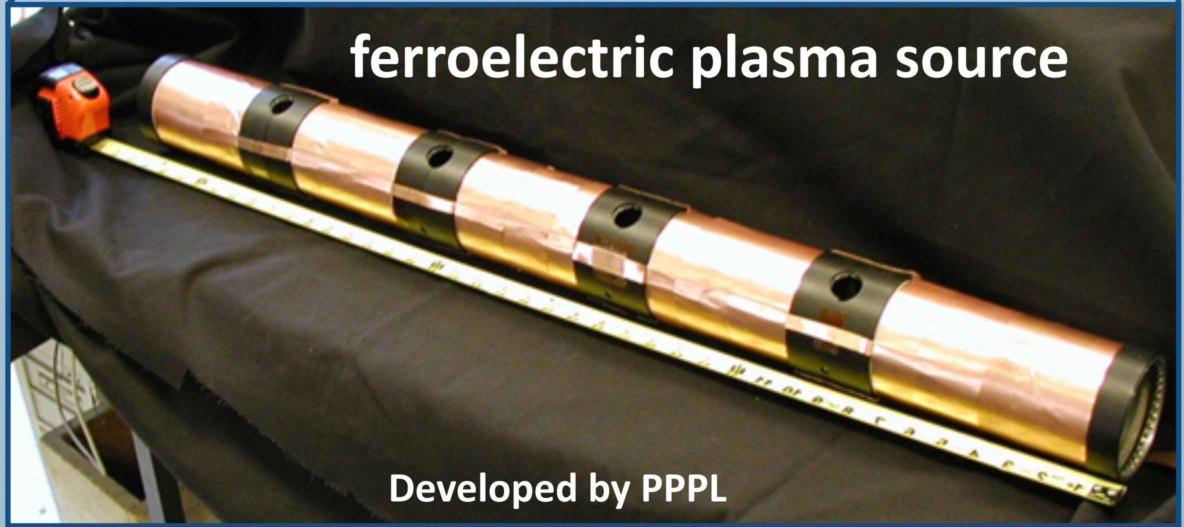
final neutralized drift compression onto target

- **electrons in plasma move to cancel the beam electric field**
- **requires $n_{\mathrm{plasma}} > n_{\mathrm{beam}}$ for this to work well**

see A. Friedman, *et al.*, *Phys. Plasmas* **17**, 056704 (2010)

NDCX-II plasma sources will be based on NDCX-I design



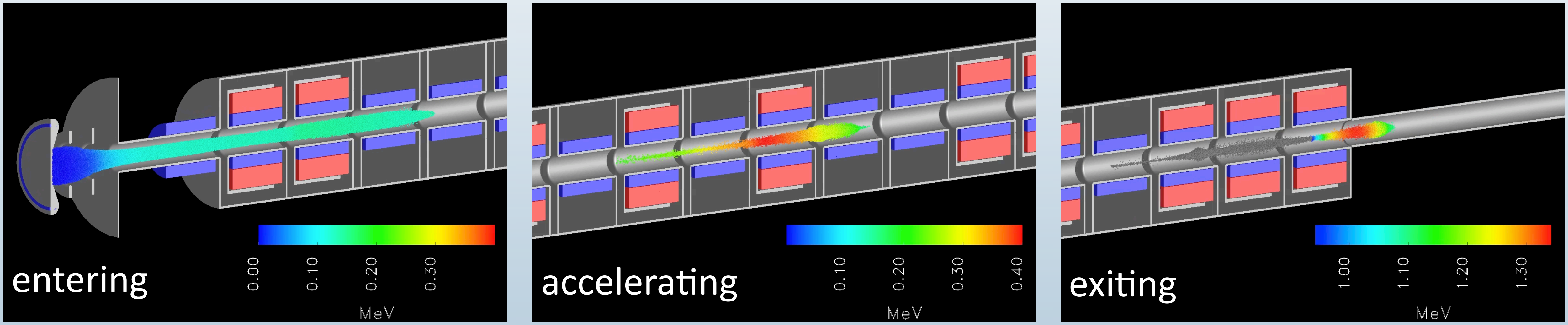


NDCX-II will be far more capable than NDCX-I

	NDCX-I (typical bunched beam)	NDCX-II 12-cell (r,z simulation)
Ion species	K^+ (A=39)	Li^+ (A=7)
Total charge	15 nC	50 nC
Ion kinetic energy	0.3 MeV	1.25 MeV
Focal radius (containing 50% of beam)	2 mm	0.6 mm
Bunch duration (FWHM)	2 ns	0.6 ns
Peak current	3 A	38 A
Peak fluence (time integrated)	0.03 J/cm^2	8.6 J/cm^2
Fluence within a 0.1 mm diameter spot	0.03 J/cm^2 (50 ns window)	5.3 J/cm^2 (0.57 ns window)
Fluence within 50% focal radius and FWHM duration ($E_{kinetic}$ x I x t / area)	0.014 J/cm^2	1.0 J/cm^2

NDCX-II estimates are from (r,z) Warp runs (no misalignments), and assume 1 mA/cm^2 emission, no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, perfect neutralization, and a uniform non-depleted source; they also assume no fine energy correction (e.g., tuning the final tilt waveforms)

Simulations enabled development of the NDCX-II physics design



40ga24-12

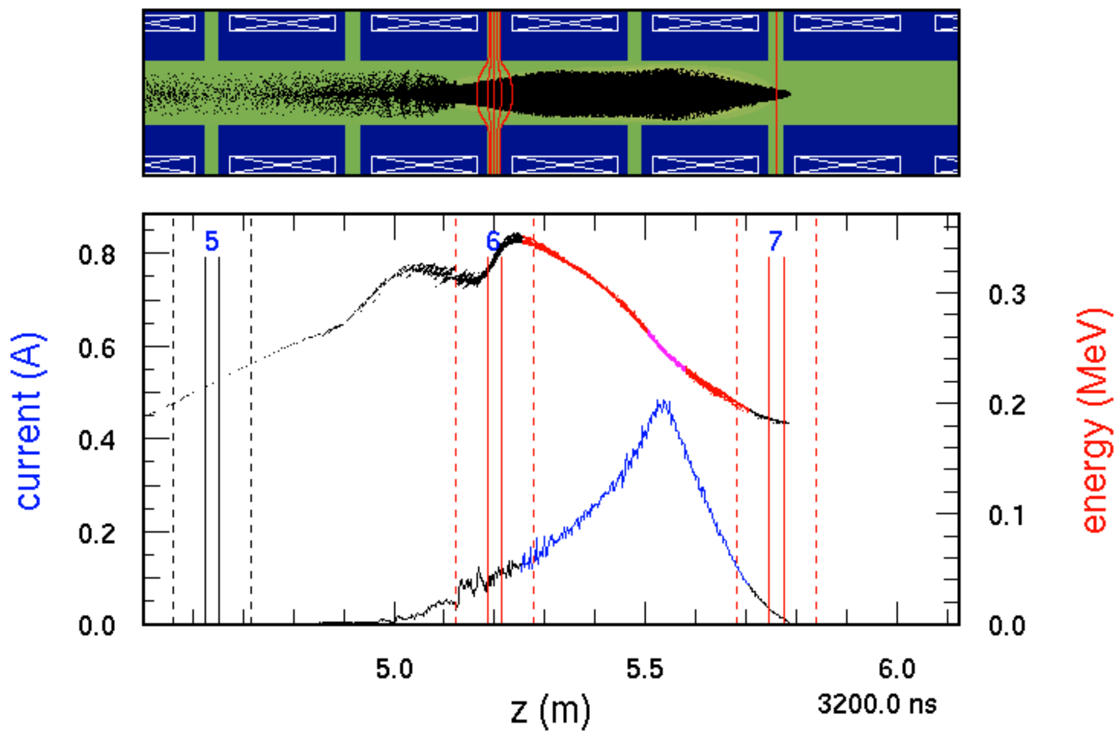
- new, fast 1-D (longitudinal) particle-in-cell code ASP facilitates finding attractive operating points within the large parameter space
- injector, transverse beam confinement, and final focusing are developed using the Warp code in axisymmetric (r,z) geometry
- 3-D particle-in-cell code Warp is used to assess performance in the presence of imperfections and set error tolerances

These same tools will enable detailed comparisons of beam measurements and simulations, using “synthetic diagnostics”

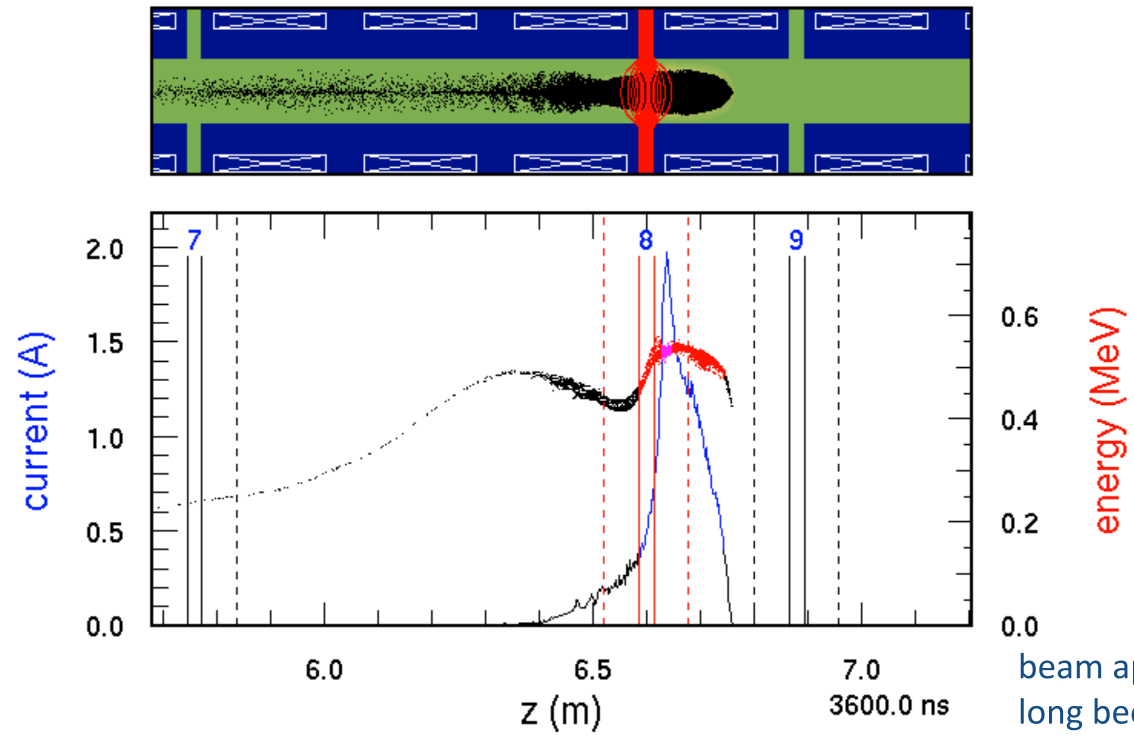
see A. Friedman, *et al.*, *Phys. Plasmas* **17**, 056704 (2010)

Snapshots from a Warp (r,z) simulation

compressing

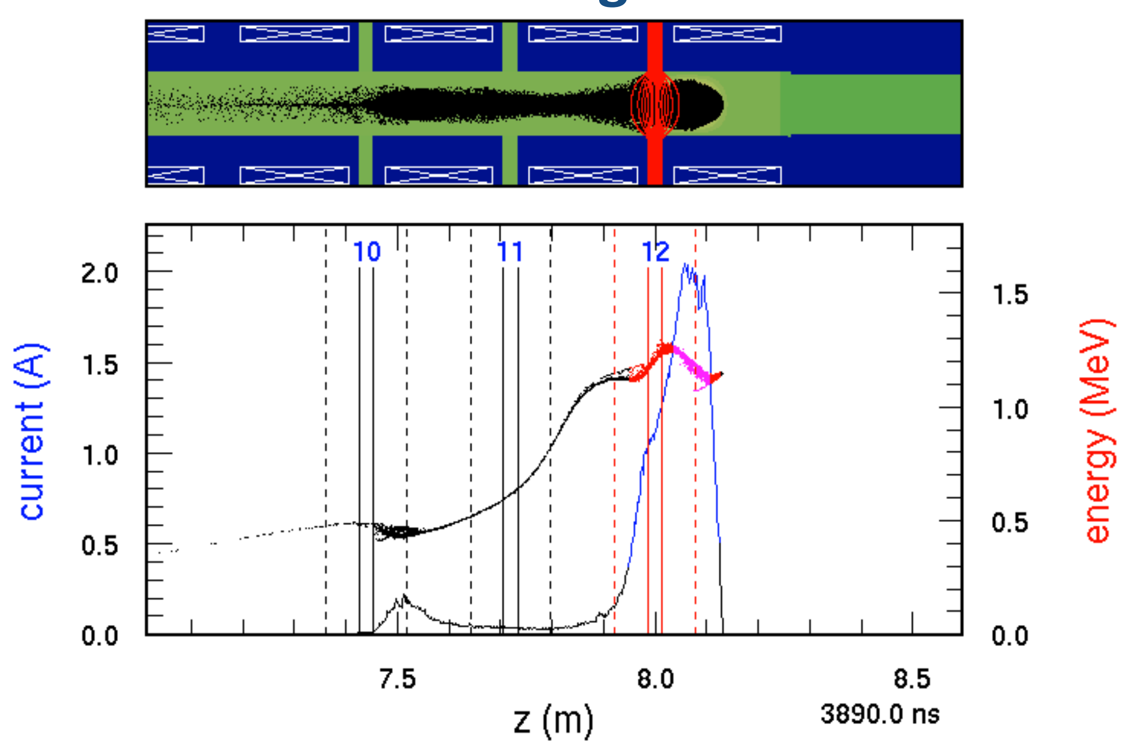


maximum compression

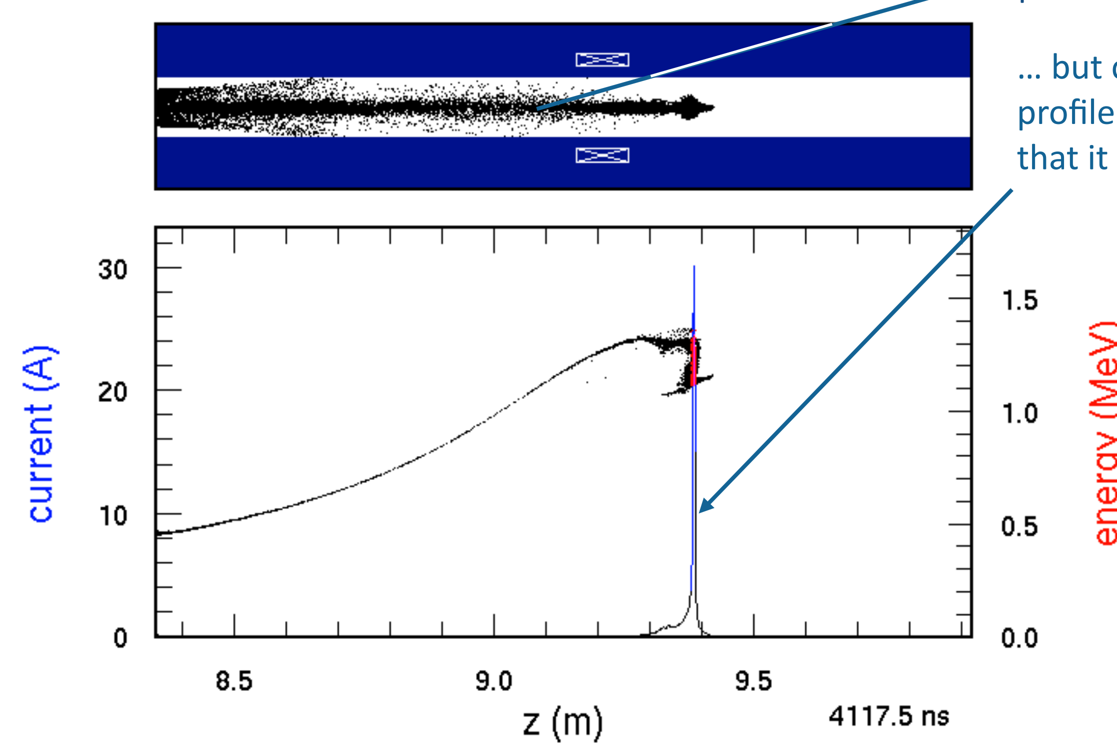


beam appears long because we plot many particles …

exiting

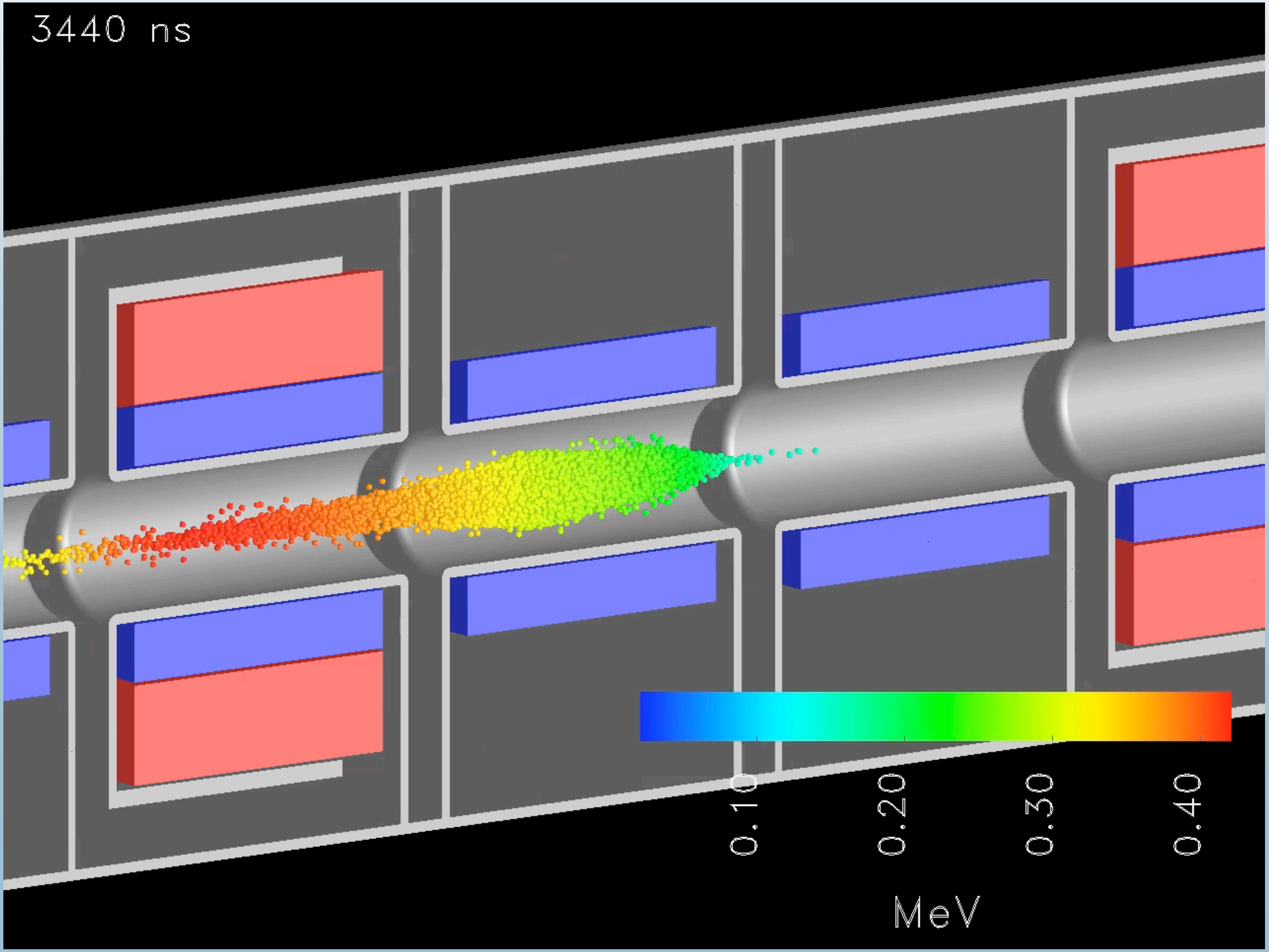


final focus

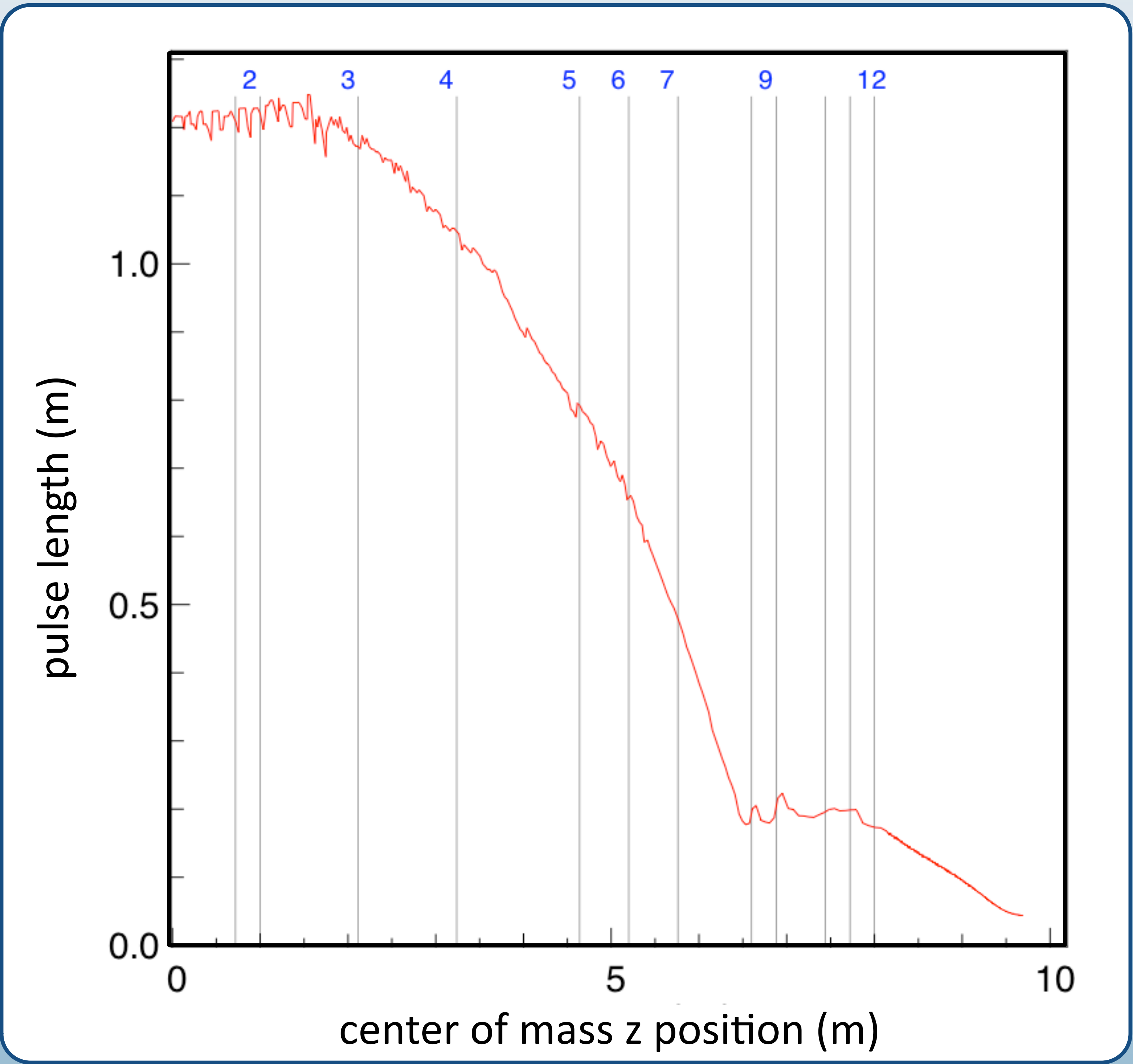


… but current profile shows that it is short

3-D Warp run of 12-cell baseline case with perfectly aligned solenoids



Pulse length vs z as calculated using 1-D ASP simulation



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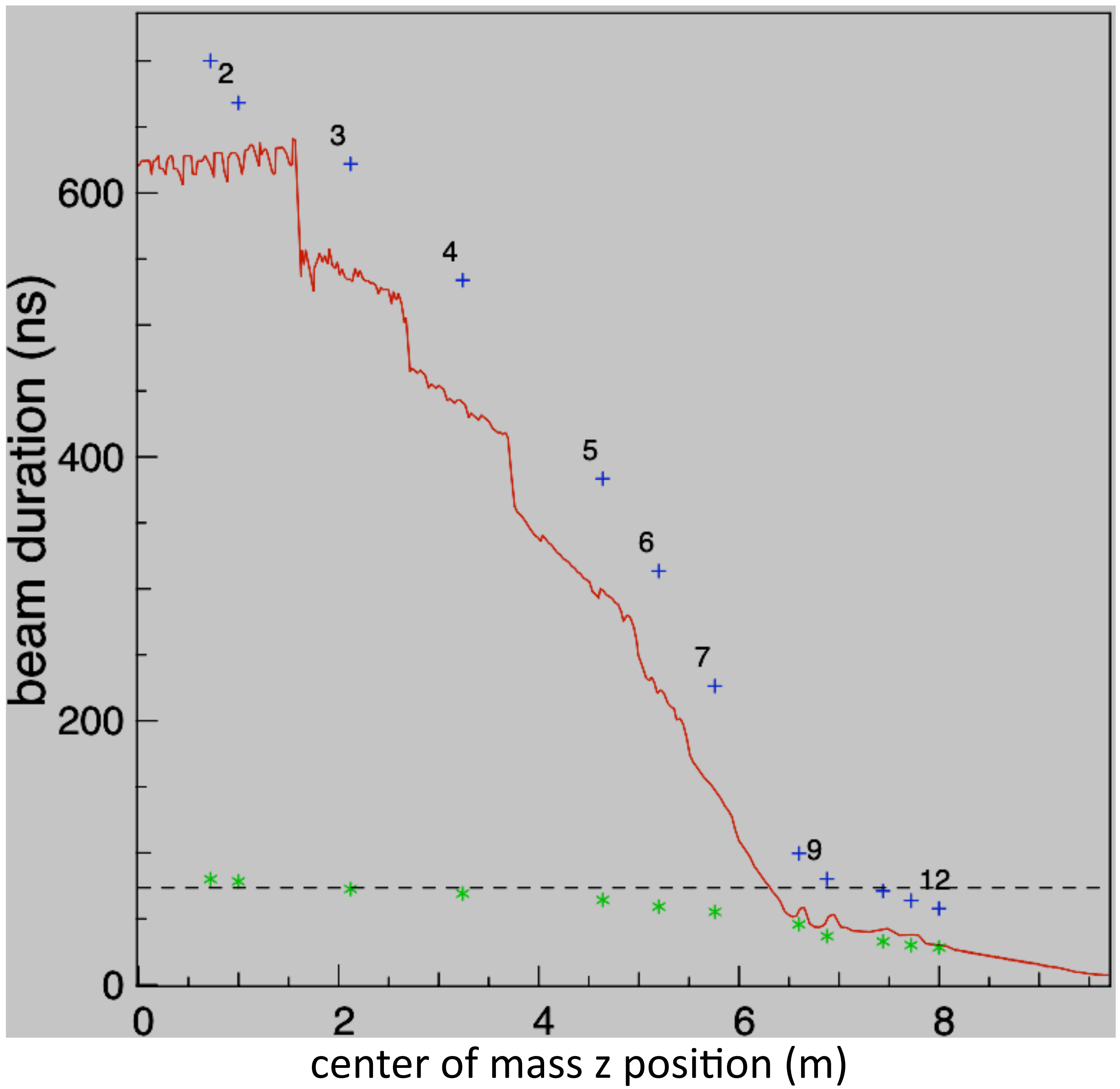
vertical lines denote centers of active acceleration gaps

Pulse duration vs z for the same 1-D ASP simulation

transit time of entire beam must be less that 70 ns to enable use of ATA pulsers



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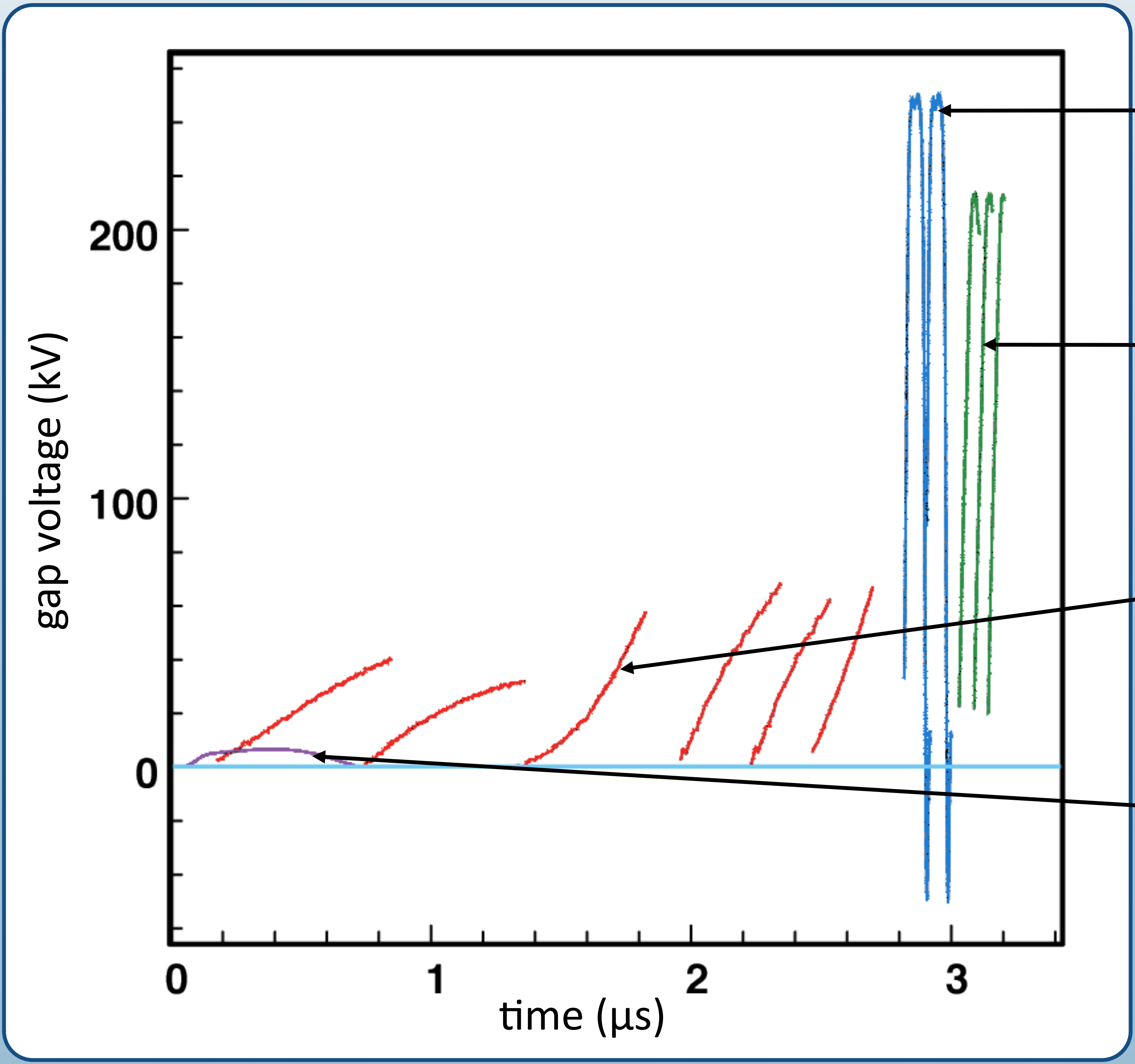
- time for entire beam to cross a plane at fixed z

* time for a single particle at mean energy to cross finite-length gap

+ time for entire beam to cross finite-length gap

Voltage waveforms for all gaps



250 kV “flat-top” measured waveform from test stand

200 kV “ramp” measured waveform from test stand

“shaped” for initial bunch compression (scaled from measured waveforms)

“shaped” to equalize beam energy after injection

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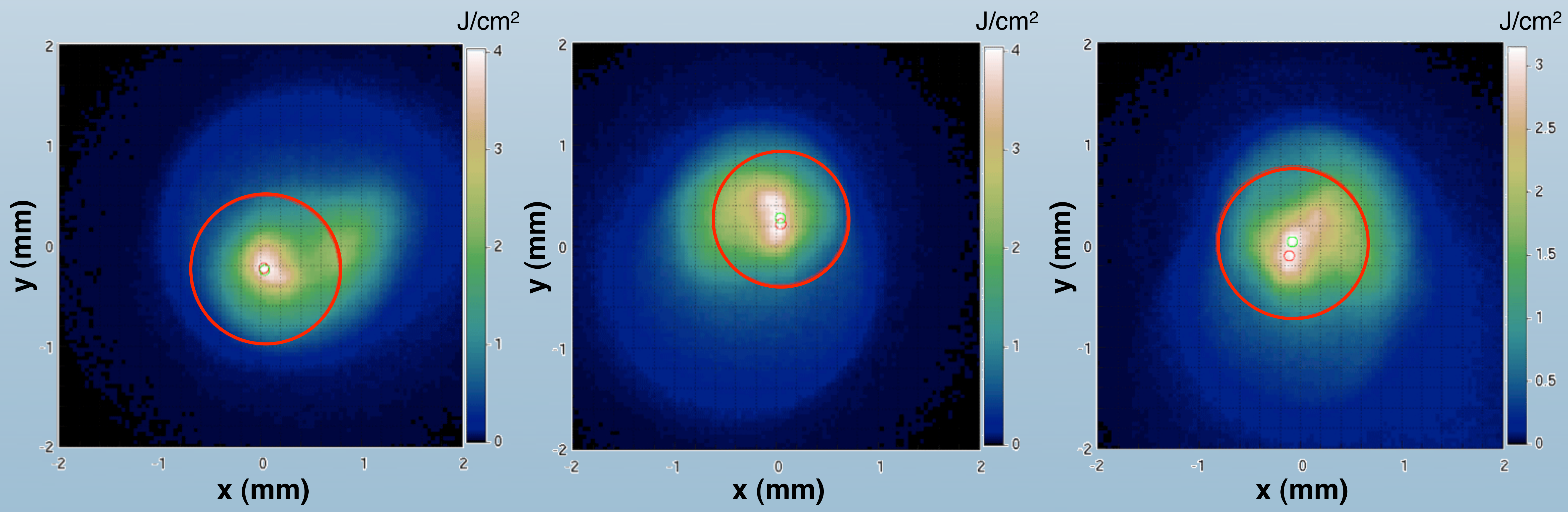
Warp runs illustrate effects of solenoid alignment errors

Plots show beam deposition for three ensembles of solenoid offsets

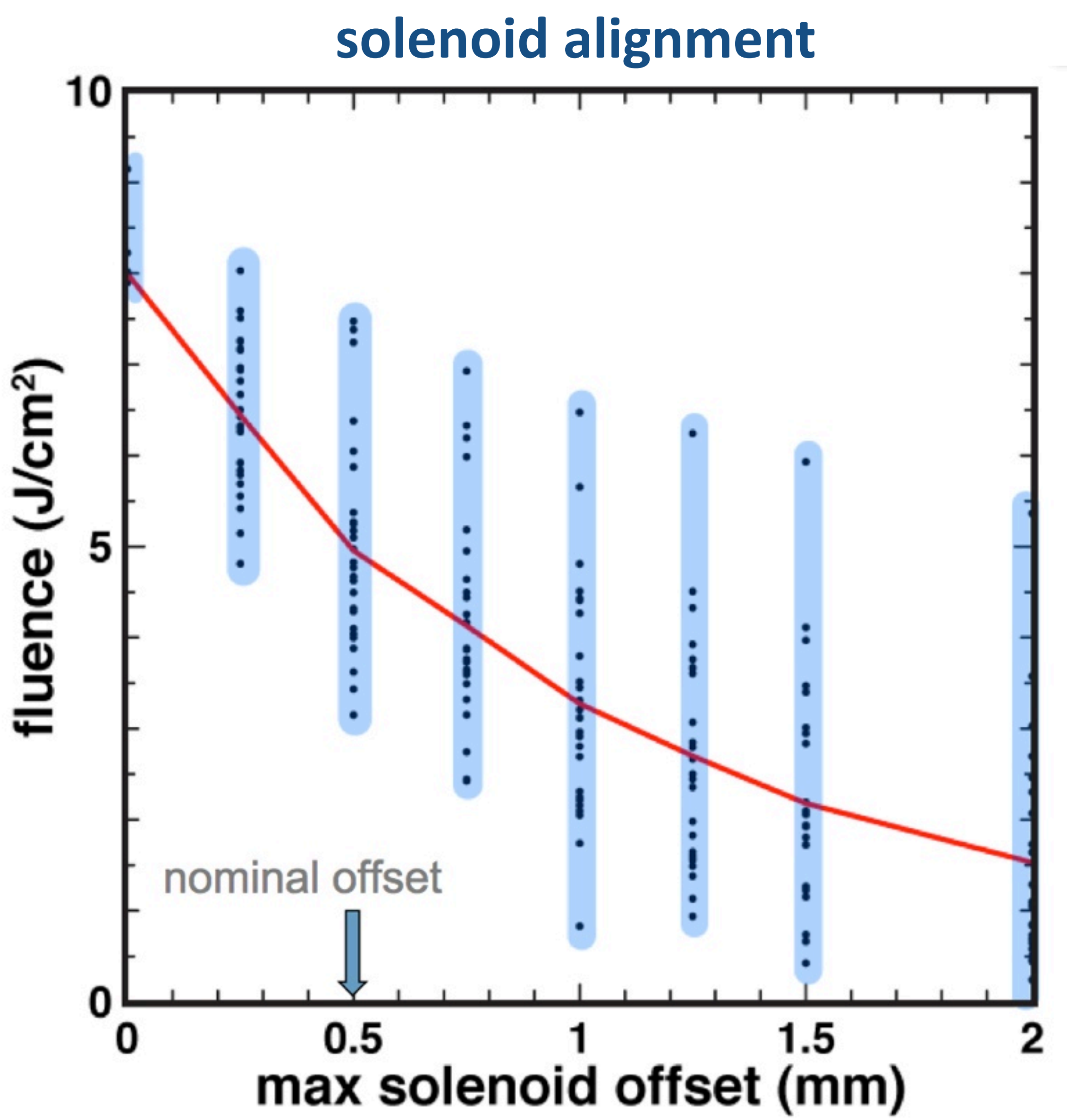
- maximum offset for each case is 0.5 mm
- red circles include half of deposited energy
- smaller circles indicate hot spots

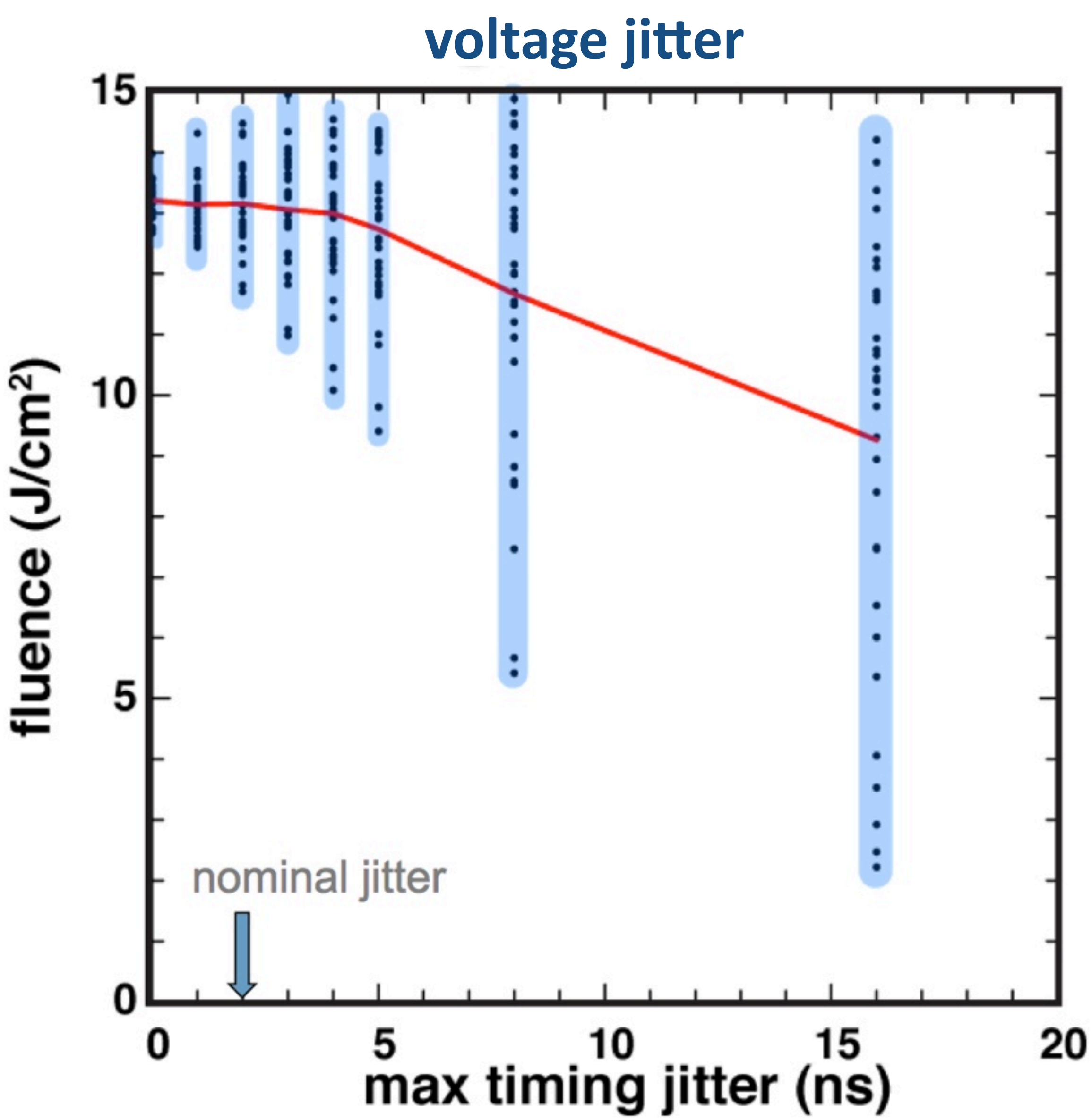


Ensembles of Warp runs have determined error tolerances

Warp studies show the NDCX-II design tolerate anticipated errors

- random offets were made to the solenoid ends (nominal tolerance is 0.5 mm)
- random timing shifts were made to acceleration voltage pulses (nominal jitter is 2 ns)





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Outline

motivation

- Why worry about energy? Why nuclear energy? Why not renewables or fission?

a fusion primer

- What's fusion? What's stopping us?
- How can we get energy from fusion? gravity vs magnetic fields vs inertia

rudiments of inertial fusion

- What are the advantages of inertial fusion?
- What are the driver options? Lasers vs ions vs electrons vs spitballs
- What are the choices in heavy-ion drivers?
- Who's doing what in heavy-ion fusion?

US inertial fusion research

- What's the direction of the US program?
- What are the main parts of a heavy-ion driver?
- What have we been doing for the last thirty years?
- What are we doing now? Introduction to NDCX-II

future research directions

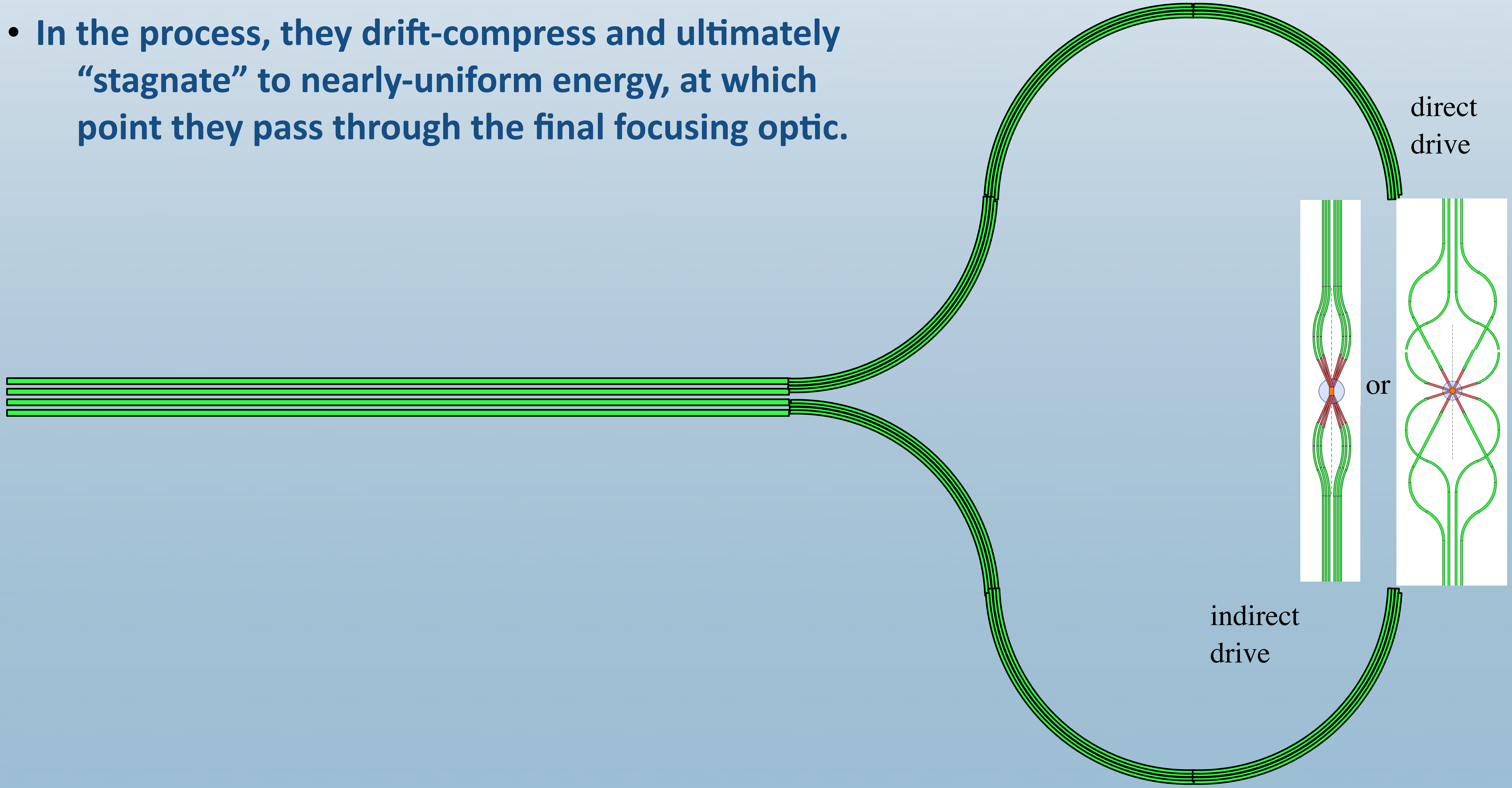
upgrades can significantly enhance NDCX-II capabilities

	NDCX-I	NDCX-II			
		12-cell (baseline)	15-cell	18-cell	21-cell
ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
total charge	15 nC	50 nC	50 nC	50 nC	50 nC
ion kinetic energy	0.3 MeV	1.2 MeV	1.7 MeV	2.4 MeV	3.1 MeV
focal radius (50% of beam)	2 mm	0.6 mm	0.6 mm	0.6 mm	0.7 mm
duration (bi-parabolic measure = √2 FWHM)	2.8 ns	0.9 ns	0.4 ns	0.3 ns	0.4 ns
peak current	3 A	36 A	73 A	93 A	86 A
peak fluence (time integrated)	0.03 J/cm^2	13 J/cm^2	19 J/cm^2	14 J/cm^2	22 J/cm^2
fluence within 0.1 mm diameter, within duration		8 J/cm^2	11 J/cm^2	10 J/cm^2	17 J/cm^2
focal spot figure of merit		0.18	0.48	0.48	0.64

Caveats: these are from axisymmetric (r,z) Warp runs without misalignments, assuming uniform 1 mA/cm^2 emission, front-end pulses that match the design, and perfect neutralization; they use only measured Blumlein waveforms

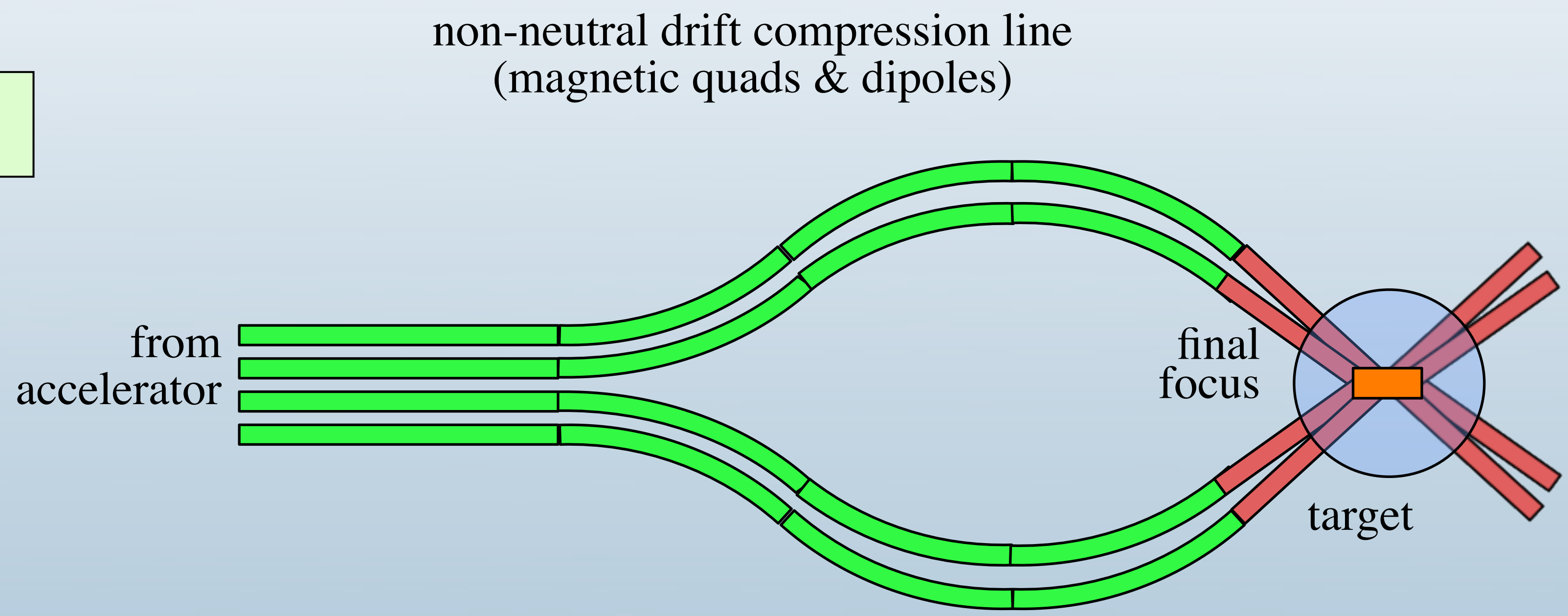
NDCX-II experiments can model the final sections of a driver

- In the final section of the driver, the beams are separated so that they may converge onto the target in an appropriate pattern.
- In the process, they drift-compress and ultimately "stagnate" to nearly-uniform energy, at which point they pass through the final focusing optic.

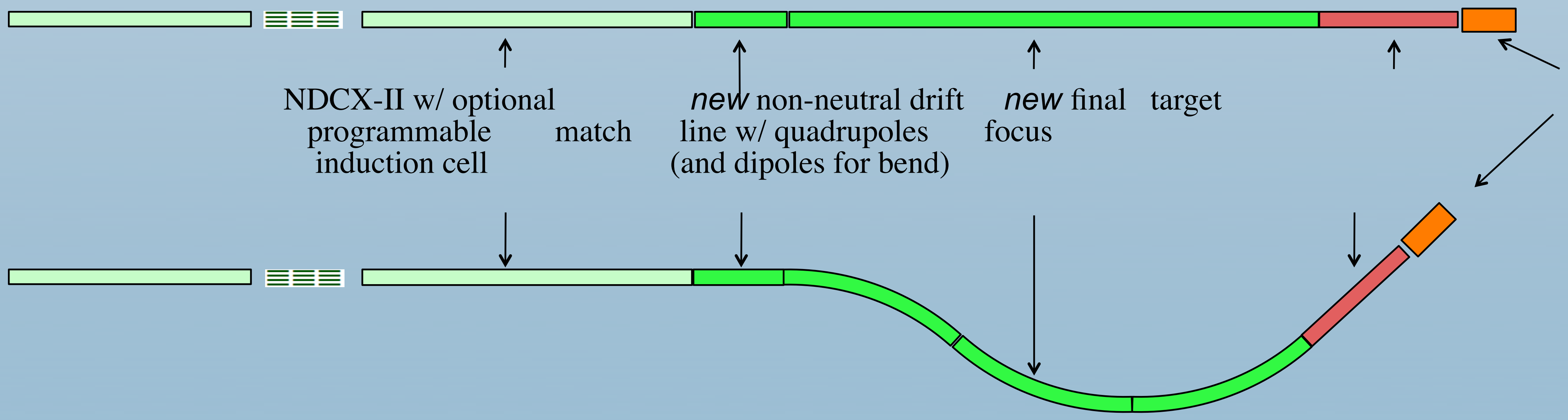


Experiments on NDCX-II can explore non-neutral compression, bending, and focusing of beams in driver-like geometry

In a driver …

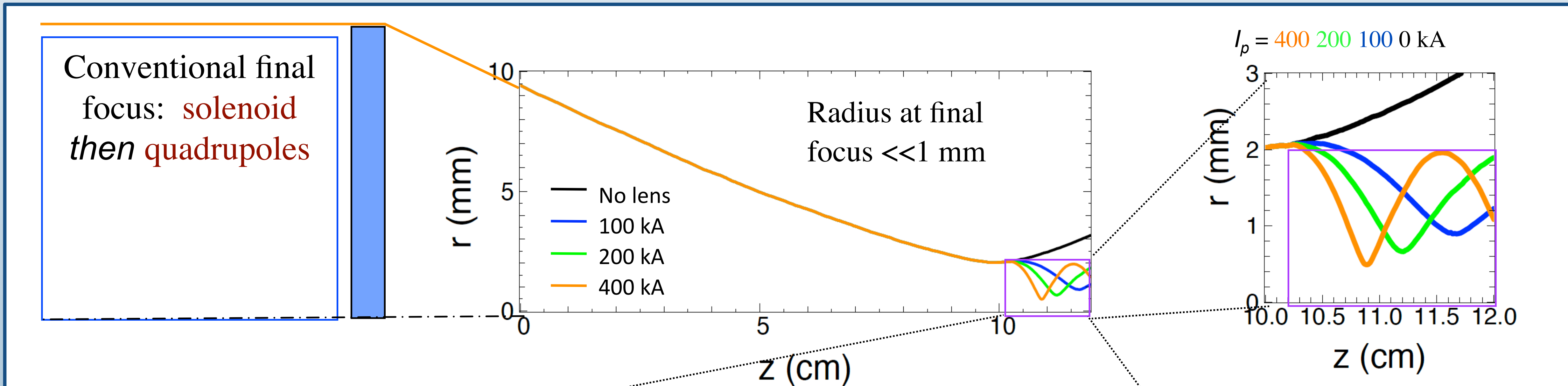


On NDCX-II, two configurations to test …

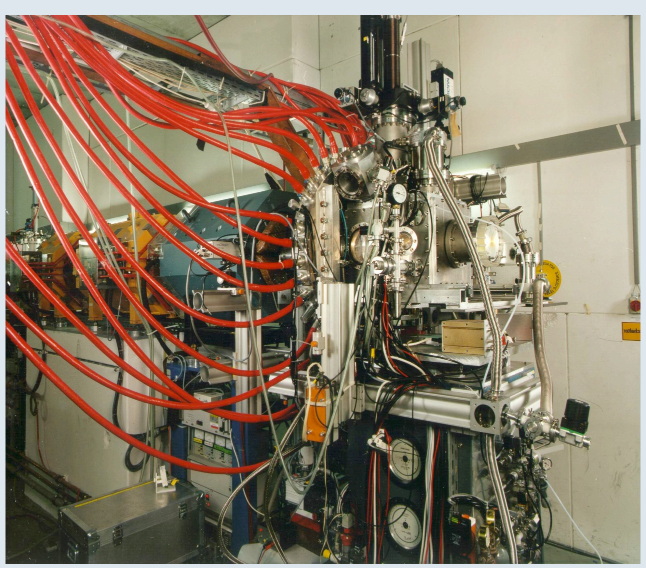


NDCX-II experiments can explore two-stage final focusing

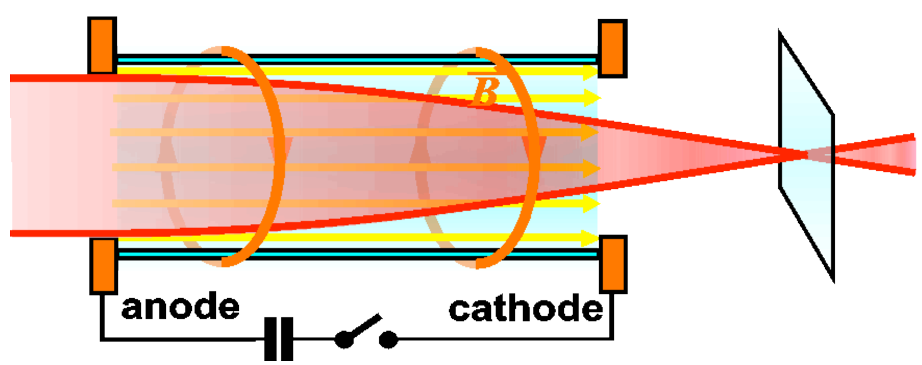
conventional final focus can be followed by a second-stage B_θ plasma lens



GSI plasma lens (I_p=240 kA)

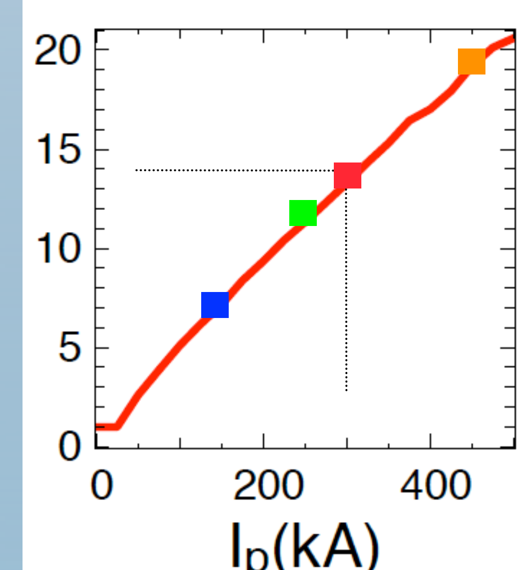


Windowless B_θ plasma lens



2 mm radius
0.5-1.5 cm length
I_p = 100-500 kA

Fluence increase **>10x** at I_p=250 kA



From Warp simulation (ideal B_θ, neutralization)

A balanced IFE research program includes

Target physics & design

Direct and indirect drive targets for power plant and for an intermediate target and accelerator physics facility

Symmetry requirements, beam pointing

Stability

Accelerator physics & driver design:

Multi-beam ion sources, injection, matching

Focusing elements: solenoids; magnetic & electric quadrupoles

Acceleration

Neutralized & un-neutralized drift compression

Halo formation and control

Achromatic focusing systems

Time dependent chromatic correction

Final focusing, reactor interface, design

Reactor and driver interface

Tritium breeding

Radiation shielding

Liquid protection

Enabling technology

Pulsed power

Insulators (e.g.: glassy ceramics, embedded rings)

Solenoid & quadrupole magnets

Superconducting materials (Nb3Sn)

Focusing arrays

Reactor materials and components

- Items in red are explored (to varying degrees) on the baseline NDCX-II accelerator.
- Items in green are to be explored via add-ons.

Fusion...

...still the energy of the future after sixty years